Independent Forestry Panel

Public submission

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THE GREENS

4 November 2024

The Independent Forestry Panel
Peter Duncan AM
Professor Mary O'Kane AC
The Hon. Mick Veitch

Submission to the Consultation on the Forest Industry Action Plan

I am writing to address critical issues related to the unsustainable logging practices currently affecting NSW's public native forests. Native forest management in NSW is at a crossroads, and urgent action is required to ensure the sustainability of these forests, the preservation of biodiversity, the protection of cultural heritage, and the resilience of the landscape against climate change.

In my 35 years of engagement with environment, planning and natural resources law, policy and politics in NSW, as an advocate, public interest environmental lawyer and now an MP, I find the fact that we are still logging our small but significant public forest estate nothing short of environmental vandalism. There has never been a clearer case for ending the logging of our public native forests. With a wealth of compelling scientific and economic evidence, we must act to protect these invaluable resources.

Sustainability of Current and Future Forestry Operations

Native forest logging is an unsustainable, unprofitable industry, where 90% of native trees felled are left to decay, burnt, or reduced to low-quality pulp products. This industry, heavily reliant on public funds, has cost the NSW Treasury $44 million over the last three financial years, with projections showing a continued decline in expected revenue over the forward estimates.

Forestry Corporation's estimates for harvestable timber volumes are consistently inflated, leading to overharvesting and a decline in yield by approximately 40% since 2010. In 2018, the removal of protections for mature trees led to intensified logging to extract more timber from dwindling native forests. This practice depletes biomass and reduces carbon storage while simultaneously destroying mature trees that provide essential habitats.

Native forests are habitats for 174 species in NSW that rely on tree hollows for nesting and dens. The removal of mature trees disrupts the creation of these hollows, which take decades or even centuries to form. The loss of such habitats has cascading impacts on biodiversity, increasing the likelihood of species decline and local extinctions. Over half, representing 29 million hectares(ha), of pre-1788 native forest and woodland vegetation in NSW has been lost. Of the remaining 25 million ha, 9 million ha is estimated to be degraded.

The environmental impacts extend beyond biodiversity. Logging practices raise fire risks, intensify erosion, pollute waterways, and allow invasive species to proliferate. Logging disrupts the natural function of streams and rivers, reducing water quality and availability - a crucial concern for communities and ecosystems reliant on these water sources.

The last 25 years have seen fire frequency and severity rise alarmingly, culminating in the catastrophic 2019–2020 bushfires, which scorched 60% of NSW's native forests. These fires had lasting, detrimental effects on forest health. However, despite recommendations from the Natural Resources Commission (NRC) for a moratorium on logging in severely burnt areas, these guidelines were disregarded at the time. Instead, logging intensified, stripping forests of crucial mature trees, degrading soil health, and worsening the ecosystem's resilience.

The sustainability science, relied upon by the Department of Primary Industries (DPI) and the Forestry Corporation to continue logging, is compromised by vested interests and significant parts are being refuted by genuinely independent science. The acoustic testing for koalas in logged forests, as an example, has been found to be inaccurate and with faulty assumptions. Contrary to the evidence that DPI relies on to justify native forest logging, koala populations are much more likely to be vulnerable to impacts from logging than previously assumed.

Environmental and Cultural Values of Forests

NSW's native forests have enormous environmental and cultural significance. Intact forests provide essential ecosystem services, including rainfall generation, air purification, and landscape cooling. The role of mature forests in supporting pollination is critical for maintaining biodiversity across NSW, benefiting both forest ecosystems and adjacent agricultural lands.

The cultural and spiritual value of these forests cannot be overstated. For First Nations people, forests are sacred landscapes, deeply tied to cultural knowledge, practices, and identity. First Nations communities have a profound, ongoing connection to native forests, which serve as living sites of heritage and practice. NSW's native forests provide cultural, recreational, and health benefits for both First Nations and non-First Nations communities, fostering a sense of pride and connection to place.

The stakes are particularly high for threatened species, with 150 species in NSW directly impacted by logging and 269 nationally listed threatened species depending on these forests for survival. The broad-scale impacts of native forest logging are compromising the survival of entire ecosystems, underscoring the urgent need for alternative management approaches.
Native forests also play a vital role in the hydrological cycle, generating rainfall, reducing temperatures, and recycling water. As climate change drives more erratic rainfall and intensifies droughts, mature forests' abilities to retain moisture and cool landscapes become ever more crucial. Logging disrupts this balance: initial runoff may increase briefly after logging, but water tables decline dramatically in the long term as regrowth demands up to 50% more water than mature forests.

With water security becoming a paramount concern for regional NSW, the scientific evidence linking forest preservation to reliable water supplies is undeniable. Native forest preservation is a practical and economically beneficial strategy to protect NSW's water systems, making it essential to transition away from logging.

Demand for Timber Products and Market Dynamics

Native forest logging accounted for just 9% of Australia's total log production in 2023, contributing only 2.4 million cubic metres of timber out of a national total of 25 million cubic metres. Remarkably, half of the logs harvested from native forests were processed as wood chips and exported. In the hardwood plantation sector, a staggering 87% of logs also ended up as wood chips, with only 8% meeting the higher-value saw and veneer log standards.

Given the low demand for native forest timber, it is clear that native forests are no longer required to meet Australia's timber needs. The timber needs of housing, construction, mining, transport, and retail can be met through alternative materials, such as sawn softwood and composite timber products made from softwoods. Essential Energy's recent decision to phase out the use of native forest timber for power poles is further evidence of the declining demand for native forest products.

In NSW, just 1,000 workers are directly employed in native forest logging. Transitioning these workers into alternative employment is not only achievable but would cost the state only $244 million over 10 years. With the Blueprint Institute's Branching Out report predicting at least $294 million in revenue from alternative uses of North Coast forests by 2040, the economic potential of native forest management without logging far outweighs the meagre returns of continuing the current logging regime.

Future of Softwood and Hardwood Plantations and Private Native Forestry

Currently, plantations provide 91% of Australia's total log production. NSW has an opportunity to meet future timber needs by promoting sustainable plantation practices, prioritising saw and veneer log production over wood chip exports. By focusing on higher-value timber products from plantations, NSW can relieve pressure on native forests and meet market demands in a more sustainable and economically viable manner.

The softwood plantation division of the NSW Forestry Corporation returned $113 million over the last 3 financial years, proving that softwood plantations are both profitable and sustainable when managed responsibly.

The state's subsidies for Forestry Corporation's native forest logging distort the market and create an artificial dependence on unsustainable practices. Private land harvesting for luxury native hardwood products should be strictly limited and regulated, ensuring that public native forests are preserved and restored.

Role of State Forests in Delivering Environmental, Economic, and Social Outcomes

NSW's public native forests span 2 million hectares and provide diverse ecological and economic benefits. These forests support water quality in catchments, enhance tourism, and offer essential carbon storage and climate resilience. Allowing native forests to regenerate naturally has proven economic benefits, often surpassing the economic value of timber production from logging.

Publicly funded subsidies are sustaining an industry that operates at a financial loss, with the Forestry Corporation's native forest hardwood division receiving tens of millions in equity injections to cover its losses. The people of NSW should not be required to subsidise an industry that damages biodiversity and sacrifices critical habitats. Instead, investing in First Nations ranger programs, like the Githabul Rangers, has shown success in restoring forest health and improving ecosystem services through Indigenous knowledge and stewardship.

Opportunities for Carbon and Biodiversity Benefits in Climate Adaptation

Ending native forest logging would reduce annual carbon emissions in NSW by an estimated 3.6 million tonnes, equivalent to taking 840,000 cars off the road each year. Forest logging more than halves the amount of stored carbon in a forest, while allowing forests to remain intact or regenerate would make substantial contributions to NSW's emissions reduction targets.

Long-lasting wood products constitute only 4–8% of a forest's carbon, with the rest returning to the atmosphere as logging debris decays. Protecting NSW's native forests could prevent 76 million tonnes of carbon emissions by 2050—equivalent to $2.7 billion in climate mitigation benefits. Given that forests take centuries to recapture lost carbon, it is urgent that we prioritise protecting and regenerating NSW's native forests to address our climate crisis.

Healthy forests are inherently more resilient to climate-driven threats such as fires and extreme weather. As climate change intensifies, preserving unlogged forests becomes increasingly important for building resilience within NSW's landscapes. Logged forests, on the other hand, are significantly more susceptible to catastrophic fires, erosion, and loss of biodiversity, underscoring the urgent need to halt these unsustainable practices.

Conclusion

Ending public native forest logging in NSW is not only scientifically and economically sound but also politically feasible. With ample economic modelling, international precedents, and bipartisan potential, there is a clear pathway for the Labor Government to phase out this destructive practice. Public native forests, when left intact, offer immense economic, environmental, and cultural benefits. By aligning with scientific guidance and public sentiment, we can protect these precious ecosystems, support regional communities, and build resilience against climate change.

I urge the Independent Forestry Panel to recommend an end to public native forest logging in NSW, allowing these vital landscapes to continue providing for generations to come.

Yours sincerely

[redacted]

Sue Higginson
Member of the Legislative Council & Solicitor

Attachments:

- **Frontier Economics,** *Transition support for the NSW native forest sector*
- **Blueprint Institute,** *Branching Out: Exploring Alternate Land Use Options for the Native Forests of NSW*
- **Natural Resources Commission,** *Final Report: Coastal IFOA operations post 2019/20 wildfires*
- **Natural Resources Commission,** *NSW Forest Monitoring and Improvement Program: Insights for NSW forest outcomes and management*
- **North East Forest Alliance,** *Clearing Our Rainfall Away*
- **The Tree Projects,** *NSW Forest Carbon: An Effective Climate Change Solution*
- **Smith & Pile,** *Koala Density, habitat, conservation, and response to logging in eucalyptus forest; a review and critical evaluation of call monitoring*
- **Conservation Science and Practice,** *Shifting baselines clarify the impact of contemporary logging on forest-dependent threatened species*

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Cover page to the report *Transition support for the NSW native forest sector* by Frontier Economics

Forests provide homes for wildlife, store carbon, make rain, purify water, provide multiple benefits for Indigenous communities, support nature-based businesses, attract tourists, and benefit people's physical and mental health. They provide solutions to the nature and climate crises. Forests are explicitly recognised as a nature-based solution to climate change in the *Glasgow Climate Pact* and the *Glasgow Leaders' Declaration on Forests and Land Use*. The draft *UN Convention on Biological Diversity post-2020 Global Biodiversity Framework* includes goals and targets for protecting and expanding terrestrial ecosystems, which include forests.

Forests face tipping points due to deforestation and forest degradation, global heating and invasive species. As New South Wales (NSW) becomes hotter and drier, more tall wet sclerophyll forests will be replaced by woodlands, shrubland and even grasslands.

The unprecedented 2019/20 bushfires brought into stark reality the future of forests of NSW, and the businesses and communities which rely upon them. The fires burnt 4.8 million hectares including 64% of state forests. The fires had a devastating toll on wildlife, forest communities and the timber industry. Koalas and Greater Gliders are now endangered species in NSW.

WWF-Australia's *Regenerate Australia* is our vision and program of action to ensure our environment, people and wildlife thrive. WWF's *Towards Two Billion Trees* program is part of this vision and aims to save and grow two billion trees nationally by 2030.

This includes seeking a just transition out of industrial scale native forest logging to a timber and pulp industry based on plantations grown on already cleared land and managed to the highest standards.

As Australia's largest conservation organisation WWF-Australia has a material and legitimate interest in how forests are managed in NSW, especially on public lands.

NSW is the second largest producer of logs harvested from native forests in Australia. Victoria and Western Australia have made commitments to transition out of native forest logging, however NSW is yet to do so.

WWF-Australia considers that the forestry-to-plantations transition in NSW is inevitable, necessary, and overdue. Such a transition would support various NSW government initiatives: cutting emissions by 50% by 2030, doubling koala numbers by 2050, handback of lands to Indigenous communities, growth in nature-based tourism in the regions, increasing supply of low-carbon housing construction materials in the long term, reducing plastic pollution, and protecting and enhancing natural capital.

This transition should be efficient and equitable, end harmful and wasteful subsidies, minimise potential negative impacts and maximise the positive impacts on communities and the economy. Structural adjustment programs established by the governments of Victoria and Western Australia to support the transition from native forest logging to plantations demonstrates this is possible.

Therefore, WWF-Australia commissioned Frontier Economics to analyse the likely impact of completing the transition from native forest logging to plantations in NSW, and the structural adjustment design principles which could support a transition for the sector.

This report was not commissioned to ignite or exacerbate ‘forestry wars’. Instead, it is designed to inform and motivate critical solution-focussed discussions, ideally led by the NSW Government.

WWF-Australia calls for a just transition from forestry-to-plantations, that engages industry, along with climate scientists and eminent ecologists. We also recognise that substantial structural adjustment funding will be required, as proposed in this report.

We urge the NSW government to engage forest and plantation stakeholders to carefully and sensitively consider the drivers and opportunities for completing the forestry-to-plantations transition.

The transition must benefit both people and nature.

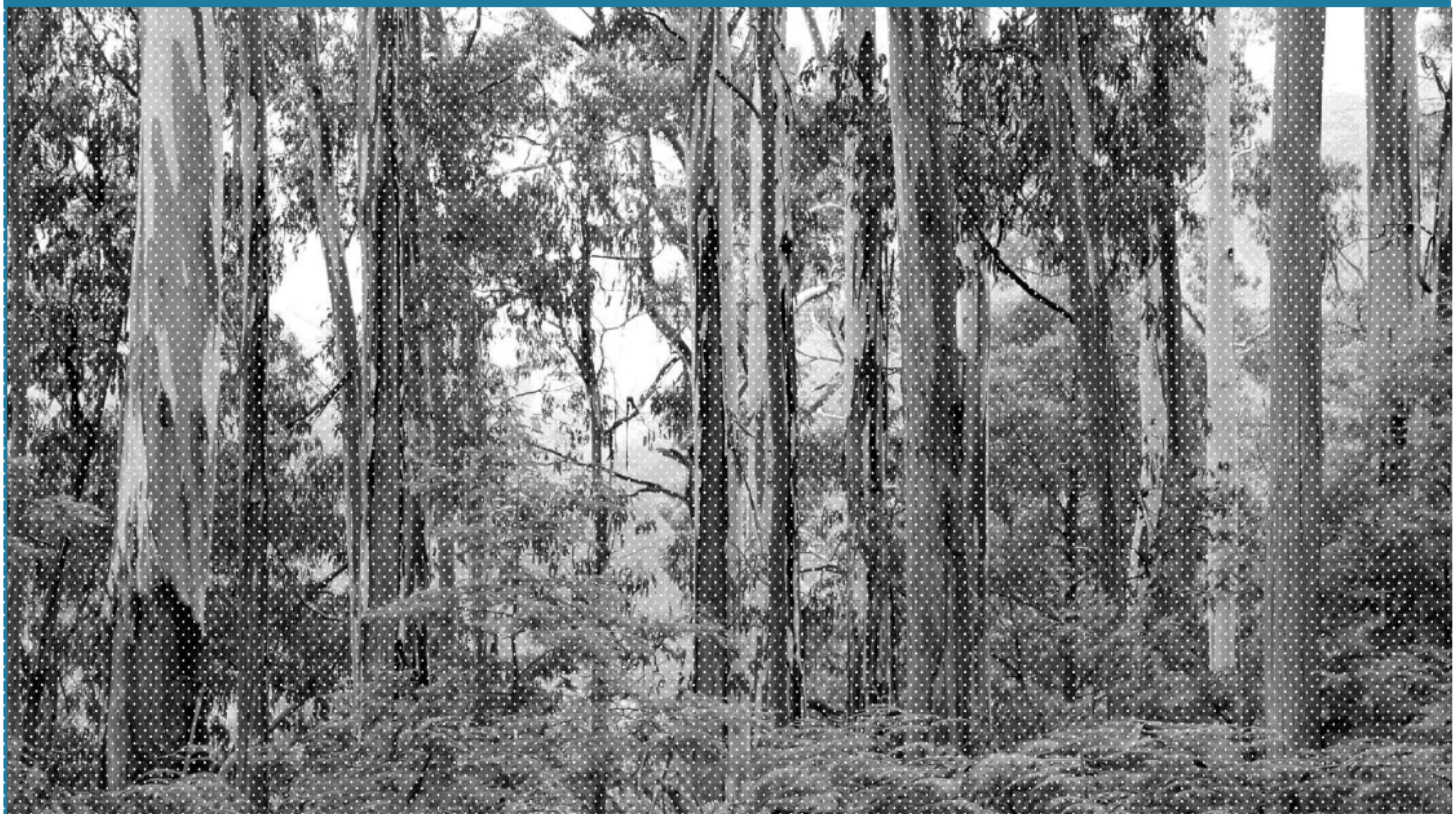
It should be co-designed with the timber and plantations sectors, forest communities, First Nations and conservation organisations.

On behalf of our 2+ million supporters, we seek time-bound leadership on this issue, mindful of all that was lost in the recent 2019-20 bushfires, cognisant more native forest is being lost in NSW, and optimistic for a better future for forests and the timber and pulp industry.

WWF-Australia commends this report to the NSW government.

Rachel Lowry
Acting CEO
WWF-Australia

8 August 2022



Transition support for the NSW native forest sector

A report for the World Wide Fund for Nature–Australia | 8 August 2022

Contents

Tables

Figures

Boxes

Executive summary

The New South Wales (NSW) native forest sector has been contracting over a long period as publicly provided wood supply has fallen to more sustainable levels. The 2019–20 Black Summer fires has compounded this trend, significantly reducing sustainable wood supplies, particularly in the South Coast and Tumut regions. This shock to the sector, economy and regional communities – combined with an increased recognition of the significantly higher value that standing native forests offer in comparison to logging – provides an opportunity to reconsider the best use of NSW's native forest resource. Other states including Victoria and Western Australia facing similar issues have made a decision to end the native forest logging.

In this context, Frontier Economics was engaged by WWF–Australia to develop an understanding of the likely impact of Forestry Corporation of NSW (FCNSW) ceasing native forest logging and the structural adjustment design principles which could support a transition for the sector.

Financial returns and economic contribution of FCNSW native forest business is small

This report finds that FCNSW's native forest logging business appears to offer poor financial returns to NSW taxpayers and some parts of the hardwood business are unlikely to be covering costs. The volume of wood supplied by FCNSW's native forest business has been falling, and is unlikely to return to historic levels of production given the current state of the native forest resource and the increasing impacts of climate change.

In line with the reduction of available wood supply, the economic contribution of FCNSW's native forest business in terms of employment and economic contribution in NSW has also fallen to a modest level. Across selected regions with a public native forest logging footprint, ABS data shows that the hardwood and softwood forestry sectors (both private and public) contribute a small and often declining share of regional employment, tending to contribute less than 1% and but ranging from 0% –1.3% for Forestry and Logging and 0.4% –2.5% for Wood Product Manufacturing.

Narrowing down the focus to the public native forestry sector, we estimate direct employment numbers in FCNSW, harvest/haulage and mills associated with this business to be in the order of 1,070 across the State (made up of Northern, Southern and Western region employments levels at 590, 332, and up to 150 employees, respectively).

Design of structural adjustment support

Despite the relatively small economic contribution public native forestry makes in NSW, the businesses and jobs are highly valued in the regional economies. As a result comprehensive packages of structural adjustment to support impacted employees, firms and communities have been put in place historically and would be required as part of ceasing the remaining native forest logging activity by FCNSW.

There is a broad consistency in the design of public native forest logging structural adjustment packages across jurisdictions, including:

- Support for workers through redundancy top-up payments and resources for retraining
- Support for harvest/haulage contractors and mills though capital redundancy payments, grants for transition and remediation, and contract buy-backs
- Longer term funding to diversify local regional economies and create jobs

- Longer term support for increased investment in plantation resources.

Estimated cost of structural adjustment support

Estimates are made of the costs associated with a structural adjustment package designed along similar lines to those adopted in other jurisdictions, should a decision be made to end public native forestry in NSW. It is assumed the adjustment package would be implemented from 2028-29 once the majority of the current Wood Supply Agreements (WSAs) with processors have expired.

The elements of the package that involve direct support payments and grants from government are estimated and assessed separately from potential investments to develop plantations. The former represent a direct budgetary cost to government. The latter is an investment decision for FCNSW (and potentially other businesses) that could be expected to make a long term financial return.

The estimated cost of the government-funded structural adjustment is $302 million in total. This includes:

- Up front structural adjustment funding of $244 million, which it is assumed would be incurred at the beginning of 2028-29. This is the payments to support worker redundancies and retraining, capital redundancies and WSA buy-backs, and
- Structural adjustment funding for regional economic diversification of $58 million, which is assumed to be spent over a 10-year period. Assuming this is spent in equal amounts over the 10 years to 2038-39, this provides a net present value (NPV)[1] cost of $47 million.

Therefore, the NPV cost of the whole package is $291 million over the 10-year period from 2028-29 to 2038-39.

Plantation expansion cost

It is challenging to estimate the cost of establish new plantations without more detailed analysis of the likely location and species. However, based on information from ABARES, to establish 33,000 ha of new plantation (comparable to the size of the current FCNSW hardwood plantation estate) would be approximately:

- $158 million upfront for land and establishment for softwood planation expansion (and around NPV$204 million in terms of whole of life costs over 30 years), and
- $165 million upfront for land and establishment for hardwood planation expansion (and around NPV$233 million in terms of whole of life costs over 25 years).

The Victorian and West Australian government have announced funding for plantations of $110 million (number of hectares unknown) and $350 million (for 33,000 ha as assumed above), respectively.

As noted above, the forestry sector (including FCNSW) would sensibly lead any plantation expansion in NSW based on its understanding of the best locations, appropriate size of expansion, plantation species and market needs. It is possible that the NSW government may contribute funding to expanding the plantations in NSW. However, this would need to be

[1] Net present value compares cost in a common year, in this case 2028-29. The NPV calculation assumes a 4% discount rate.

determined at a later date, and with a better understanding of whether there was a justifiable requirement for government funding.

Budgetary impact

As shown in the report, the cost of the structural adjustment package is likely to be readily outweighed by a range of positive budget impacts including avoided ongoing structural adjustment and bushfire support to the hardwood sector, avoided equity injections to FCNSW and the likelihood of increased dividends from FCNSW over time by avoiding the loss making activities of the hardwood division which have been highlighted by the Independent Pricing and Regulatory Tribunal of NSW (IPART).

Alternative employment opportunities

The transition out of public native forestry can be supported by employment growth in related regional sectors. We find that there are likely to be alternative employment opportunities for displaced workers from the native forestry sector, particularly in management of protected forest areas, recreation and tourism, plantation-based forestry work, fire and invasive species management and the management of carbon and biodiversity credits.

1 Context and purpose of this study

1.1 Study context

Native forest logging by Forestry Corporation of NSW (FCNSW) has been placed on a more sustainable footing in recent decades. The resulting reduction in wood supply has reduced the size of FCNSW's native forestry business and the downstream processing sector. The native forest area harvested by FCNSW has fallen from over 30,000 hectares in 2012-13 to a bit over 13,000 hectares in 2020-21.[2]

FCNSW's hardwood business has experienced long periods of unprofitability and has struggled to cover the cost of meeting some Wood Supply Agreements (WSAs). FCNSW's latest annual report shows that the Hardwood Division made a $20 million loss in 2020-21 after fire recovery expenses. In their latest annual Sustainability Report,[3] FCNSW acknowledge that the financial position of the Hardwood business is unlikely to improve for 'several years' due to reductions in wood supply and the ongoing fire impacts on the native forest estate.

While not fully transparent, there is strong evidence that the budgetary and environmental burden of effectively subsidising native forest logging operations of FCNSW are significant. At the same time there is far less community acceptance of the environmental damage associated with native forest logging,[4] including loss of precious remnant forest and native animal populations. Native forest logging also works against the NSW Government's objective to achieve a 50% reduction in greenhouse gas emissions by 2030 and achieving net zero emissions by 2050.

Importantly, the NSW community is likely to be better off if FCNSW's native forest is not logged. Recent analysis by the Australian National University (ANU) and Frontier Economics has shown that in just the South Coast and Eden areas, ceasing native forest logging would produce a net economic benefit to the state of approximately $60 million, while also reducing net greenhouse gas emissions by almost 1 million tonnes (Mt) per year over the period 2022-2041.

The small size of the native forestry sector, the cost of maintaining native forest logging operations along with the loss of social licence provides an opportunity for governments to end the logging activities of their forestry businesses and to transition communities to more productive uses of the standing forest and other resources supporting the sector. In recent years the Victorian and West Australian Governments have done just that, announcing a timetable to cease native forest logging and providing structural adjustment support to the remaining industry.

These packages have included substantial financial and training support to impacted workers, plant and equipment redundancy payments to mills and harvest and haulage contractors, business transition assistance and investment in new softwood plantations. The Victorian plans provides more than $200 million to support workers, businesses and communities and an

2 FCNSW, *2021 Sustainability Report*, p. 23.
3 FCNSW, *2021 Sustainability Report*, p. 5.
4 For example, see: Schirmer, J., Dare, L., and Mylek, M 2018, *Community perceptions of Australia's forest, wood and paper industries: implications for social license to operate*.

additional $110 million for plantation development. The WA plan includes $80 million in transition support and $350 million for softwood plantations.[5,6]

1.2 Design of structural adjustment arrangements for NSW

In this context, Frontier Economics has prepared this report for WWF–Australia that considers options for the design of appropriate structural adjustment arrangements that would accompany a decision to cease the native logging activity of FCNSW. The potential cost of the structural adjustment options, including buy-outs of WSAs and plantation establishment, are also estimated.

These costs were estimated using publicly available data, Frontier Economics did not have access to data from FCNSW or the NSW Government outside of that in the public domain.

Our approach to designing appropriate structural adjustment arrangements is based on:

- An understanding of the likely economic impact of FCNSW ceasing native forest logging, including analysis of the likely size of economic impact, the location of the economic impact and associated employment impacts.
- Principles for the sound design of structural adjustment packages including that they are well targeted, tailored to particular needs and circumstances, simple to administer, limited in duration and compatible with general safety net arrangements.
- An understanding of the design of native forestry sector structural adjustment packages in other jurisdictions and the underlying assumptions and approach that has been taken, including the expansion of plantation resources.

1.3 Report structure

The following report is structured as follows:

- Section 2 discusses the value of NSW's native forests to the community through the concept of natural capital
- Section 3 describes how the industry associated with FCNSW's native forestry business has declined over time as wood supply has fallen, and provides information on its current economic contribution to regional economies
- Section 4 provides case studies of structural adjustment support provided to the native forestry sector in Australia
- Section 5 advises on the design of a possible structural adjustment package for NSW and estimates the range of possible costs associated with the package. The net budgetary impact for NSW and alternative employment opportunities for impacted workers is also explored.

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5 The Victorian Government, *Victorian Forestry Plan*, viewed 20 May 2022, https://djpr.vic.gov.au/forestry/forestry-plan

6 WA Government 2021, McGowan Government's historic move to protect native forests. 8 September. Available at: https://www.mediastatements.wa.gov.au/Pages/McGowan/2021/09/McGowan-Governments-historic-move-to-protect-native-forests.aspx (accessed: 20 May 2022).

Additional information is provided in supporting appendices including:

- Appendix A: Supporting information on FCNSW's native forestry business
- Appendix B: Supporting information on the NSW native forestry processing sector.

2 Recognising the value of the native forest

This section briefly outlines the growing mainstream acceptance of the contribution natural capital makes to the economy. While natural capital tends to still be undervalued it is increasingly being considered in economic and business decision making.

2.1 Nature as an asset

There is increasing recognition and formalisation of nature as an asset. In 2017, the Australian National University applied the United Nations System of Environmental-Economic Accounting (SEEA) framework to the Central Highlands region in Victoria.[7,8] The SEEA framework integrates economic and environmental data to provide a more comprehensive view of the interrelationships between the economy and the environment, allowing for the benefit to be valued. In taking a thorough view on benefits the study found that, 'native forests would provide greater benefits from their ecosystem services of carbon sequestration, water yield, habitat provisioning and recreational amenity, if harvesting for timber production ceased.'[9]

Policy makers are better placed to determine the best use of NSW's native forest resource when the broader and interrelated environmental and economic value of native forests are recognised. Viewing NSW's native forest resource as a natural capital can facilitate better economic, financial, cultural and environmental outcomes for the State. Indeed, in its *Consultation Draft NSW Natural Capital Statement of Intent* (see **Box 1**) the NSW Government articulates natural capital as:[10]

> *Natural capital refers to the world's stocks of natural assets, and the services that flow from them, which include geology, soil, air, water, and all living things. It is from this natural capital that humans derive a wide range of services, often called ecosystem services, which make human life possible. The most obvious ecosystem services include food, water, plant materials used for fuel, building materials and medicines (Convention for Biological Diversity 2021). Capital has traditionally been thought of as money or any resource or asset that stores or provides value to people and the economy. Natural capital is a way of thinking about nature in much the same way as traditional capital – if we invest in it, it creates value, and if we degrade it, we limit its value.*

7 The Central Highlands region in Victoria is approximately 100 km north-east of Melbourne. The 735,655-ha area is predominantly native forest of public land – half of which is managed for wood production, and half reserved for conservation.

8 The Australian National University, 2017, Experimental Ecosystem Accounts for the Central Highlands of Victoria, Heather Keith, Michael Vardon, John Stein, Janet Stein and David Lindenmayer. https://www.nespthreatenedspecies.edu.au/publications-tools/experimental-ecosystem-accounts-for-the-central-highlands-of-victoria-full-report-high-res-40mb (accessed: 17 May 2022)

9 Threatened Species Recovery Hub, *Ecosystem Accounts in the Victorian Central Highlands*, viewed 17 May 2022, https://www.nespthreatenedspecies.edu.au/projects/ecosystem-accounts-in-the-victorian-central-highlands

10 The NSW Government, Consultation Draft NSW Natural Capital Statement of Intent, viewed 20 April 2022, https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Research/Our-science-and-research/natural-capital-statement-intent-consultation-draft-220206.pdf

Box 1: NSW Natural Capital Statement of Intent

In April 2022, the NSW government published its Consultation Draft NSW Natural Capital Statement of Intent which sets the ambition for, and approach to, sustainably managing natural capital in New South Wales.

The consultation draft acknowledges that the economic case for natural capital is growing and recognised the need for an enabling policy framework to secure opportunities and benefits for NSW, including:

- Conserving, restoring, and enhancing the State's natural environment and productive landscapes for current and future generations
- Improved economic and investment decision-making resulting in long-term sustainable land use
- Future-proofing NSW's key industries, particularly the State's primary industries.

Underpinning the NSW Government's decision-making and planning are six principles:

1. Demonstrate government leadership on natural capital that delivers both ecosystem services and productive landscape outcomes
2. Integrate natural capital considerations into NSW government decision-making
3. Realise the value of natural capital to grow resilient industries, regional communities and jobs
4. Create and incentivise investable natural capital opportunities across all tenures and scales in NSW
5. Build capability and investment readiness
6. Foster collaboration and partnerships that will unlock and accelerate natural capital markets and opportunities.

Regarding principle three, the NSW Government proposes to focus on identifying and enabling natural capital opportunities in regional NSW which can contribute to the development of new regional industries, sustainable employment and opportunities for primary producers, landholders and Aboriginal communities. This includes creating the market framework and financial incentives for the primary industries and lands sector to sequester carbon, enhance biodiversity, improve productivity through best practice, and create other economic opportunities.

Source: The NSW Government, *Natural Capital*, viewed 17 May 2022, https://www.environment.nsw.gov.au/research-and-publications/our-science-and-research/our-research/social-and-economic/natural-capital

The concept of investing and maintaining natural capital to derive value is increasingly recognised by both policymakers and the private sector.

2.2 Investing in natural capital

Nature has sometimes been viewed as a free resource leading to its overuse and degradation. A recent review by the UK government into the economics of biodiversity finds that nature is a 'blind spot' in economics, stating 'we can no longer afford for [nature] to be absent from accounting systems that dictate our national finances or ignored by economic decision makers.'[11]

Government and the private sector are responding and are increasingly seeking to quantify and mitigate these nature-related risks. Recent examples include the release of the Taskforce on Nature-related Financial Disclosures (TNFD) delivering a risk management and disclosure framework for organisations to report and act on nature-related risks,[12] Australia signing the Glasgow Leaders' Declaration on Forest and Land Use at COP26 to end deforestation by 2030,[13] Australia adopting the Glasgow Climate Pact emphasising the important of protecting, conserving, and restoring forests to mitigate greenhouse gases and protect biodiversity,[14] and the NSW Governments recent release of its *Consultation Draft NSW Natural Capital Statement of Intent.*

In the context of Australia, numerous studies have demonstrated the damage native forest logging causes to biodiversity – for example, a 2019 analysis of areas of Victoria proposed for native forest logging found it would negatively affect 70 threatened forest-dependant species.[15] Relatedly, an analysis of the fire footprint of the 2019–20 Black Summer fires found logging elevated the risk of high-severity fires.[16]

Ending public native forest logging also holds the potential to support the NSW Government's objective to a 50% reduction in greenhouse gas emissions by 2030 and achieving net zero emissions by 2050. Research by Griffith University suggests that while international climate policy now recognises forest protection as a mitigation strategy, it is not receiving sufficient attention. Griffith University finds that Tasmania has become carbon negative due to a change in forest management – a large and rapid drop in native forest logging – revealing an effective mitigation strategy that can both reduce emissions from the forest sector and increase carbon sequestration from the atmosphere.[17] Indeed, recent work by Frontier Economics and the Australian National University applied carbon modelling and, 'found that stopping native forest harvesting in the Eden and Southern RFA regions is likely to generate significant abatement' for relatively low-cost.[18]

The economic contribution of native forestry sector can be weighed against these impacts.

11 Dasgupta, P 2021, *The Economics of Biodiversity: The Dasgupta Review* (London), available at: https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review

12 TNFD, *Taskforce on Nature-related Financial Disclosures*, viewed 20 April 2022, https://tnfd.global/

13 UN Climate Change Conference UK 2021, Glasgow Leaders' Declaration on Forests and Land use, viewed 17 May 2022, https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/

14 United Nations, *Glasgow Climate Pact*, viewed 20 April 2022, https://unfccc.int/documents/310475

15 Taylor, C & Lindenmayer, D 2019, 'The adequacy of Victoria's protected areas for conserving its forest-dependant fauna', *Austral Ecology*, vol. 44, no. 6, pp. 1076–1091, available at: https://onlinelibrary.wiley.com/doi/abs/10.1111/aec.12805

16 The Australian National University, *Logging "amplified" severity of Black Summer bushfires*, viewed 20 April 2022, https://www.anu.edu.au/news/all-news/logging-amplified-severity-of-black-summer-bushfires

17 Mackey, B., Moomaw, w., Lindenmayer, D., & Keith, H. 2022. 'Net carbon accounting and reporting are a barrier to understanding the mitigation value of forest protection in developed countries'. *Environmental Research Letters*, vol. 17, no. 5, 054028. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/ac661b

18 Frontier Economics and Macintosh, A 2021, *Comparing the value of alternative uses of native forests in Southern NSW,* available at: https://www.frontier-economics.com.au/documents/2021/11/comparing-the-value-of-alternative-uses-of-native-forest-in-southern-nsw.pdf/

3 The economic contribution of the NSW native forestry sector is small

The economic contribution of FCNSW's native forest business to the NSW economy in terms of employment and value added has reduced significantly from historical levels, driven by reductions in wood supply, market forces and more recently the significant impacts of bushfire. These factors substantially reduce the up-front cost of transitioning away from public native forest logging and makes the transition achievable.

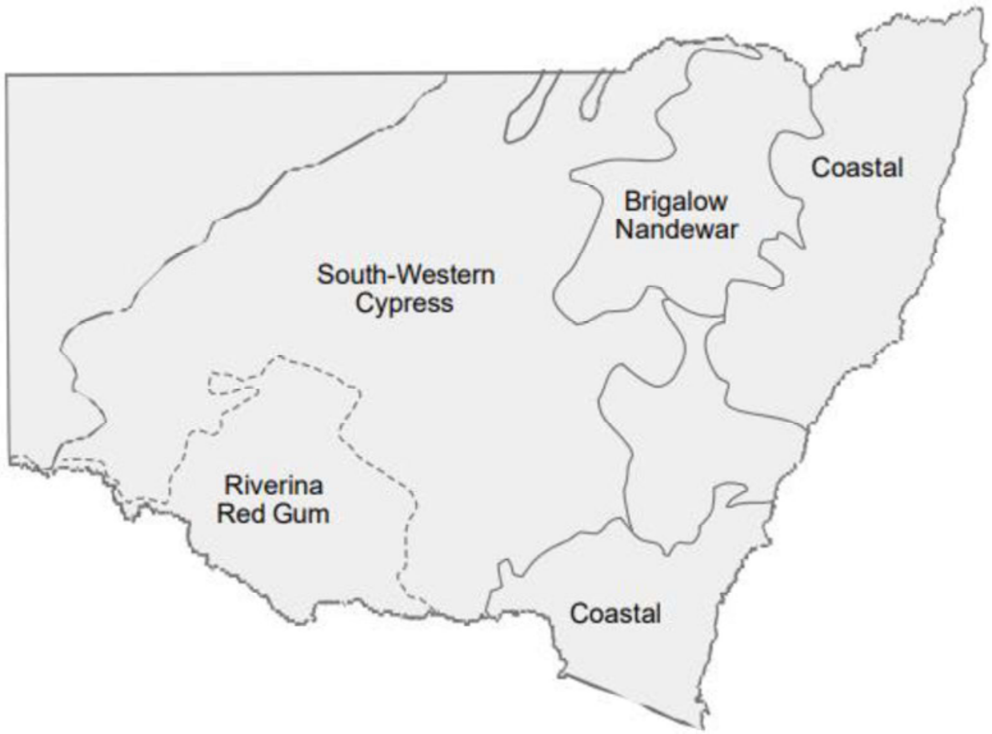
3.1 Reduction in wood supply

Since the late 1990s, stricter forest management regulations have been applied to transition native forest logging in NSW to a more sustainable footing. This commenced with the three Regional Forest Agreements (RFAs) struck between the Commonwealth and NSW Government covering the Eden, North East and Southern RFA areas. The agreements were put in place between 1999 and 2001. The agreements implemented ecologically sustainable forest management (ESFM) and sought to better balance the economic, social and environmental use of the forests. The RFAs will be in place until at least 2039 and include a five-year rolling review and extension mechanism.

In the RFA areas, timber harvesting operations are regulated by the terms of an Integrated Forestry Operations Approval (IFOA). The IFOA establish rules to protect native plants, animals, important habitat and ecosystems, soils and water in native forestry operations on public land, and set requirements to achieve ecologically sustainable forest management in NSW.

As shown in **Figure 1** there is a Coastal IFOA covering the Upper North East, Lower North East, Southern and Eden regions and three IFOAs covering the Western region (Brigalow Nandewar, South-Western Cypress and Riverina Red Gum IFOAs). The Coastal IFOA provides new rules on forest protection, including minimum standards to preserve habitat areas.

Figure 1: Integrated Forestry Operations Approval (IFOA) regions



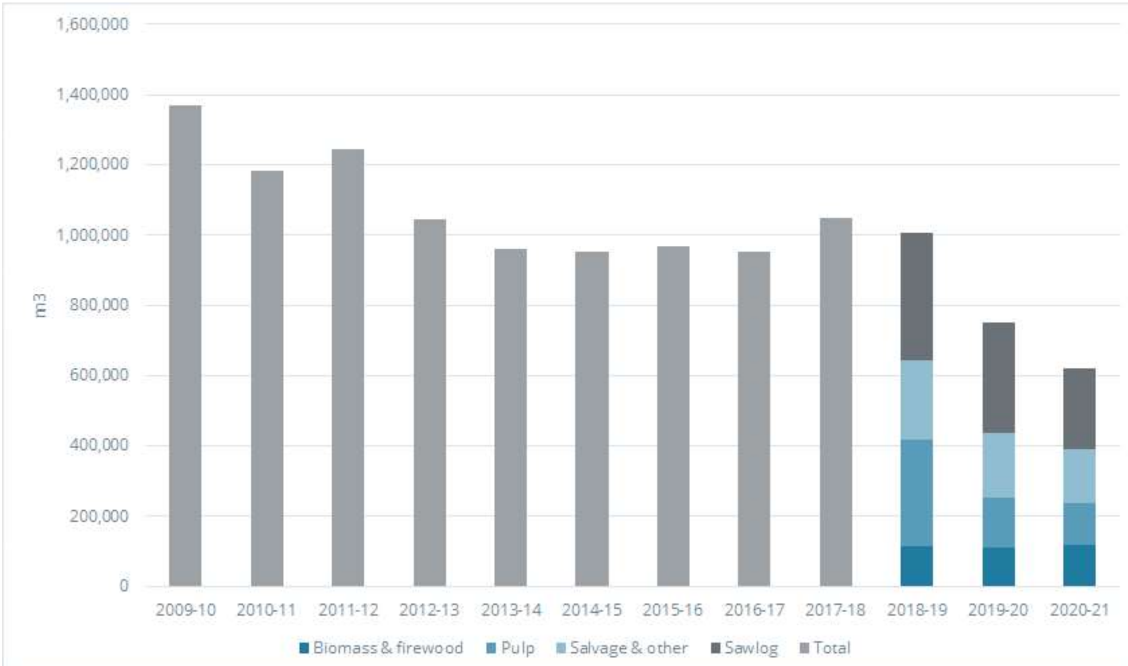
Source: NSW Environment Protection Authority, NSW Forestry Snapshot Report 2019-2020, P. 5.

The RFA process has reduced the extent of native forest available for harvest over time. This has resulted in substantial, ongoing industry structural adjustment and government funding has previously been provided to support the adjustment process.[19] As discussed in **section 4.2.1**, the NSW Government has also bought back timber allocations on the north coast which were not able to be sustainably supplied.

The reduction in native and plantation hardwood timber harvested by FCNSW is shown in **Figure 2**. Total hardwood timber production has fallen from just under 1.4 million cubic meters (m3) in 2009-10, to just over 1 million m^3 in 2018–19, and, post 2019–20 bushfires, 0.6 million m^3 in 2020-21.

19 GHD 2017, *Report for NSW Department of Primary Industries - Review of Coastal Hardwood Wood Supply Agreements*, p. 6.

Figure 2: FCNSW hardwood timber harvested



Source: FCNSW Sustainability Reports

Note: The breakdown by product is only published from 2018-29 to 2020-21.

3.2 Impact of the 2019-20 bushfires

FCNSW's ability to supply public native forest hardwood has been substantially reduced by the 2019-20 bushfires. More detail on this impact is provided in Appendix A.

Recent analysis by the NRC[20] demonstrates the profound impacts:

- The South Coast subregion has suffered severe loss of native forest which could reduce supply by up to 90%
- The expected reduction of wood supply from the Eden subregion is 40% and 35% from the Tumut subregion
- The impact on the North Coast has been less severe, but is expected to have a 20% reduction in wood supply.

The NRC reports that the loss in wood supply is undermining the viability of a number of hardwood mills, including those in Nowra and Narooma. The NRC report that 74 jobs have been stood down as at March 2021.

Given the impacts of the 2019–20 bushfires the industry is unlikely to return to historic levels of production. Some of the challenges facing the NSW hardwood industry are structural in nature, not cyclical – which is in part reflected in declining sustainable yields as calculated by FCNSW.[21]

20 NSW Natural Resources Commission 2021, *Coastal IFOA operations post 2019/20 wildfires*. This is a Cabinet-in-Confidence report that was publicly leaked.

21 NSW Forestry Corporation, *Timber volumes and modelling*, viewed 19 May 2022, https://www.forestrycorporation.com.au/sustainability/timber-volumes-and-modelling

While it will take some time for the forest and industry to recover from the recent bushfire impact, the industry's exposure to climate risk will likely grow over time.

3.3 Native forest logging's small contribution to regional economies

This section demonstrates the small and declining economic contribution to regional communities associated with FCNSW's native forest logging business.[22]

The contribution of the overall forestry sector to regional economies is small

First, Australian Bureau of Statistics (ABS) data on employment and value added contribution by local government area (LGA) is presented. This data shows the broader economic contribution associated with forestry beyond FCNSW's native forest business, as it shows aggregated employment and value added data for the private and public forestry sectors and the softwood and hardwood sectors.

The contribution of FCNSW's native forest business, which cannot be separately identified with the ABS data, is one element and hence would be materially lower than the overall employment and value added data shown.

Table 1 presents the employment and value added contribution of what the ABS refers to as forestry and logging which includes forest management/growing and harvesting. **Table 2** presents the employment and value added contribution of wood product manufacturing, which the ABS defines to include milling, chipping and wood product manufacturing.

The LGAs shown were selected as they are known to contain some public native forest activities.

The ABS data shows that the hardwood and softwood forestry sectors (both private and public) contribute a small and often declining share of regional employment, tending to contribute less than 1% and but ranging from 0% –1.3% for Forestry and Logging and 0.4% –2.5% for Wood Product Manufacturing.

Employment associated with the native forest business of FCNSW will only be a subset of this small proportion of regional employment. Hence, the economic benefits from hardwood and softwood logging, as measured by employment, are small compared to other industries in the regions – and public native forest logging, which is logically a subset of these measurements, is smaller still.

22 Based on analysis by the NSW and Commonwealth Governments. See *NSW Regional Forest Agreements Assessment of matters pertaining to renewal of Regional Forest Agreements,* NSW Department of Primary Industries, 2018, p. 299.

Table 1: Forestry and Logging (hardwood and softwood)

LGA	Employment (2020-21)	Employment (% LGA employment)	Change in employment (since 2015-16)	Value added (2020-21, $million)
Southern and Eden RFA Regions: Hardwood and softwood				
Bega Valley	181	1.4%	67	42.2
Snowy Monaro	100	1.0%	9	22
Eurobodalla	73	0.5%	18	21
Queanbeyan–Palerang	15	0.1%	1	3.4
Shoalhaven	16	0.0%	0	3.2
Upper North and Lower North RFA Regions: Hardwood and softwood				
Kyogle	21	0.7%	8	2.6
Richmond Valley	95	1.2%	29	16.3
Clarence Valley	187	1.1%	80	40.9
Bellingen	26	0.7%	5	4.1
Coffs Harbour	157	0.5%	60	38.3
Kempsey	8	0.1%	-1	1.4
Port Macquarie-Hastings	78	0.2%	-22	18.9
Mid-coast	35	0.1%	N/A	N/A

Source: Data sourced from local government profiles at https://economy.id.com.au based on data from the Australian Bureau of Statistics. Data includes softwood and hardwood employment and activity. Data for Mid-Coast LGA not available for value added, employment data is based on 2016 census.

Note: Activities included in the Forestry and Logging industry includes units mainly engaged in growing standard timber in native or plantation forests, or timber tracts, for commercial benefit and units mainly engaged in logging native of plantation forests, including felling, cutting and/or roughly hewing logs into products such as railway sleepers or posts. For more information on industry definitions see: https://www.abs.gov.au/ausstats/

Table 2: Wood Product Manufacturing (hardwood and softwood)

LGA	Employment (2020-21)	Employment (% LGA employment)	Change in employment (since 2015-16)	Value added (2020-21, $million)
Southern and Eden RFA Regions: Hardwood and softwood				
Bega Valley	73	0.5%	-64	5
Snowy Monaro	94	1.0%	-46	7.6
Eurobodalla	64	0.5%	-61	4.4
Queanbeyan–Palerang	183	1.1%	-108	12.1
Shoalhaven	294	0.7%	70	19
Upper North and Lower North RFA Regions: Hardwood and softwood				
Kyogle	79	2.5%	-19	5.2
Richmond Valley	150	1.9%	32	10
Clarence Valley	311	1.8%	-97	19.8
Bellingen	60	1.6%	-4	3.4
Coffs Harbour	124	0.4%	-39	7.1
Kempsey	66	0.6%	-14	3.7
Port Macquarie-Hastings	277	0.8%	-10	18.9
Mid-coast	179	0.6%	N/A	N/A

Source: Source: Data sourced from local government profiles at https://economy.id.com.au based on data from the Australian Bureau of Statistics. Data includes softwood and hardwood employment and activity. Data for Mid-Coast LGA not available for value added, employment data is based on 2016 census

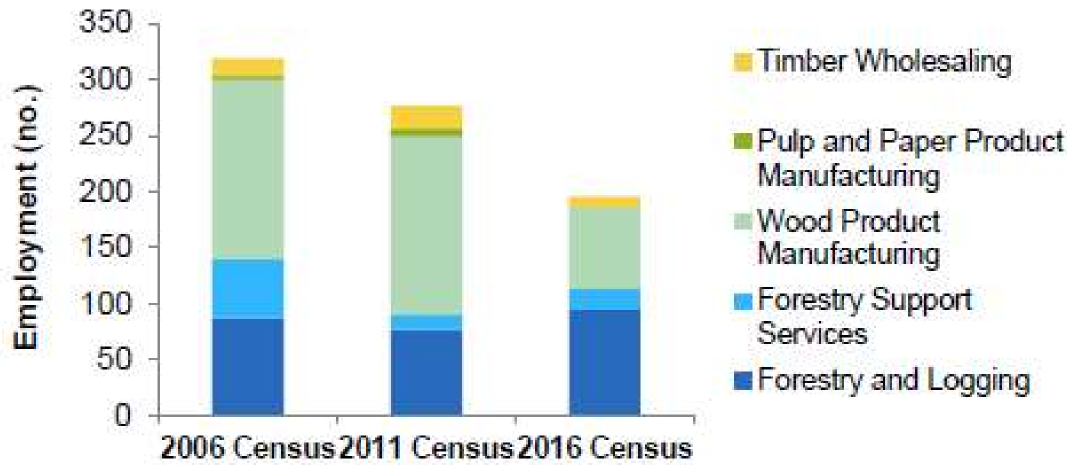
Note: Activities included in Wood Product Manufacturing include log sawmilling, wood chipping, timber resawing and dressing in addition to other wood product manufacturing (such as prefabricated wooden building manufacturing, wooden structural fitting and component manufacturing, veneer and plywood manufacturing, etc.). For more information on industry definitions see: https://www.abs.gov.au/ausstats/

Native forest-related employment has been declining significantly

Employment associated with FCNSW's native forest business is concentrated in certain LGAs. Examining these LGAs give us insight into the declining economic contribution of the native forest sector in particular.

Within the Eden RFA, native forest activity is best represented by Bega Valley LGA data. **Figure 3** shows that this employment declined by 39% over the 10 year period to 2016.

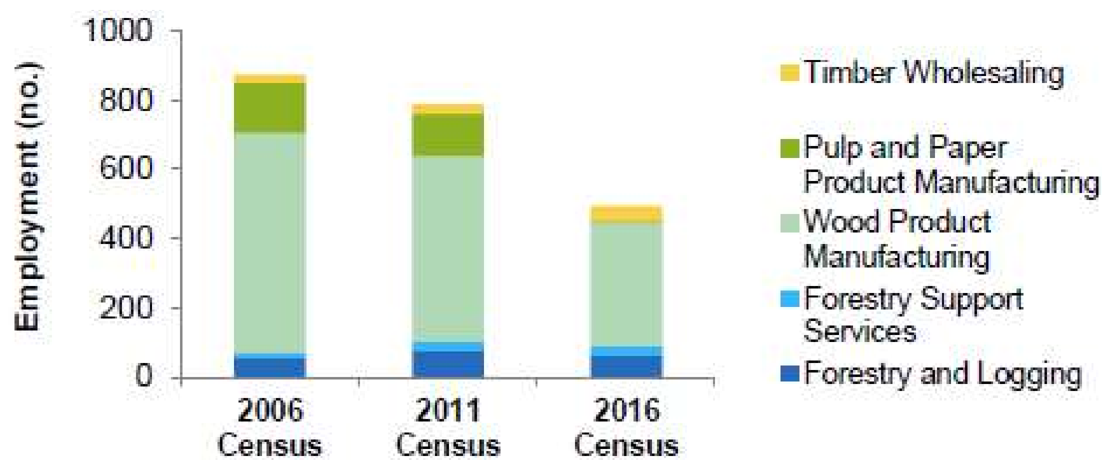
Figure 3: Direct hardwood and softwood employment Eden RFA (Bega Valley LGA)



Source: NSW Department of Primary Industries 2018, NSW Regional Forest Agreements – Assessment of matters pertaining to renewal of NSW Regional Forest Agreements, Aust 2018, p. 300.

Within the Southern RFA, the hardwood sector (plantation and native forest) can be reasonably represented by data for Eurobodalla, Shoalhaven and Queanbeyan-Palerang Regional LGAs. **Figure 4** shows that in these LGAs the decline in employment was 27% over the 10 year period to 2016.

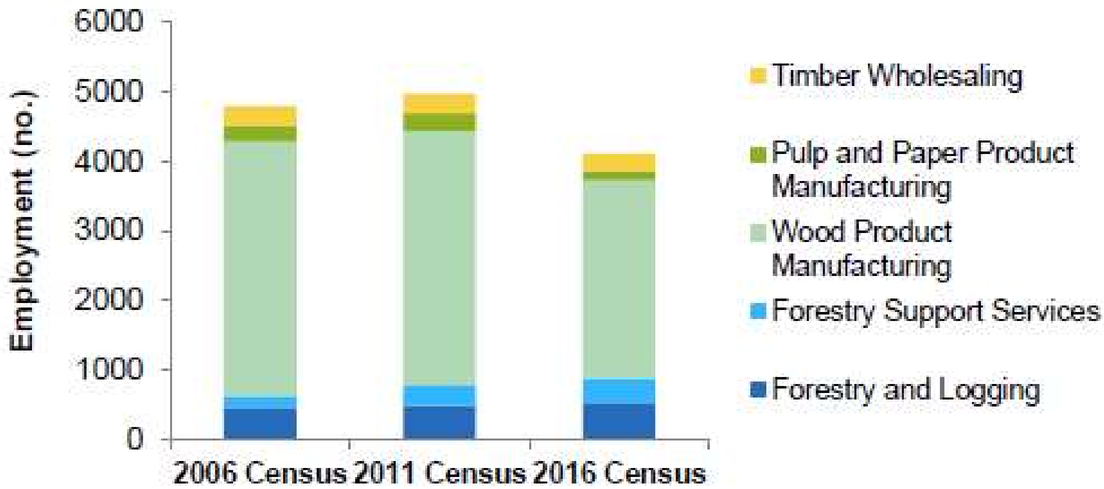
Figure 4: Direct hardwood and softwood employment in Southern RFA



Source: NSW Department of Primary Industries 2018, NSW Regional Forest Agreements – Assessment of matters pertaining to renewal of NSW Regional Forest Agreements, Aust 2018, p. 301.

Of the three NSW RFA regions, employment in the North East RFA region is likely to be the most significant for native forest logging. As shown in **Figure 5**, employment in this region has fluctuated, peaking in the 2011 Census. However, between 2006 and 2016, there has been an overall reduction in employment of 14%.

Figure 5: Direct hardwood and softwood employment in North East RFA



Source: NSW Department of Primary Industries 2018, NSW Regional Forest Agreements – Assessment of matters pertaining to renewal of NSW Regional Forest Agreements, Aust 2018, p. 301.

Across the Eden, Southern and North Coast RFA regions, employment in hardwood and softwood forestry and logging is broadly lower than that involved in downstream manufacturing activities. Employment in downstream manufacturing activities may not be materially exposed to a cessation in native forest logging. For example, pulp logs can be substituted by wood products from plantation forests and recycled paper, and plantations can provide some substitute sawlog products.

Current direct employment associated with FCNSW native forest logging is estimated to be just over 1,000 employees across NSW

The NSW NRC provides credible data on employment associated with the native forest business of FCNSW in the coastal IFOA regions. This captures the bulk of FCNSW's native forestry business.

The NRC estimate that the number of employees associated with FCNSW's coastal native forestry business – including FCNSW staff, harvest and haulage contractor staff and primary processors (hardwood forest mills and chipping) – is 332 in the South Coast sub regions and 590 in the North Coast sub regions.[23]

For FCNSW's other native forestry areas in the Western IFOA regions, Frontier Economics estimate that there are no more than 150 employees, accounting for FCSNW, harvest and haulage and processor employees. Further elaboration on these 'bottom up' estimates are contained in **Attachment B**.

This means that across NSW, direct employment associated with FCNSW's native forestry business is estimated to be in the order of 1,070 employees.

[23] NRC 2021, *Advice on Coastal IFOA operations post-2019-20 wildfires, Final Report*, June.

4 Case studies of native forestry structural adjustment support

This section provides a review of forestry industry structural adjustment packages.

4.1 Structural adjustment policies as an appropriate economic transition tool

Structural adjustment refers to compositional shifts in the economy, including in the relative size of industries, workforce characteristics and the value and mix of economic activity. The sources of structural adjustment are diverse, and include government policy and reform, as well as non-policy drivers such as technology, market conditions, or environmental conditions.

Regional economic performance is dependant, among other factors, on the capacity of the regional economy to adapt and be resilient to ongoing structural adjustment. Broadly speaking, Australian and State governments have a suite of existing measures under the social security, tax, training and job services systems to assist community and businesses when faced with economic disruptions.[24] These measures are not designed to handle all eventualities, and additional support measures are sometimes warranted.

Inherent to structural adjustment policies is the concept of a fair and efficient economic transition.[25] Circumstances which can justify the use of additional measures include:[26]

- Equity or fairness: The case for additional support can rest on a reform imposing an identifiable and sizeable burden on a specific group, particularly in the case of unanticipated shocks or changes to well defined property rights.
- Efficiency: Intervention can improve the efficiency of economic transition to a new model of growth. For example, reforms that result in sizeable economic shocks to a particular region can have adverse, compounding, and persistent flow-on socio-economic effects.

In the case of public native forest logging, other jurisdictions have deemed it necessary to adopt structural adjustment packages to support employees, firms and communities during the transition away from native logging to plantation-based logging. The remainder of this section surveys structural adjustment packages in the native forestry industry.

24 Australian Government Productivity Commission December 2017, *Transitioning Regional Economies Productivity Commission Study Report*, available at: https://www.pc.gov.au/inquiries/completed/transitioning-regions/report/transitioning-regions-report.pdf

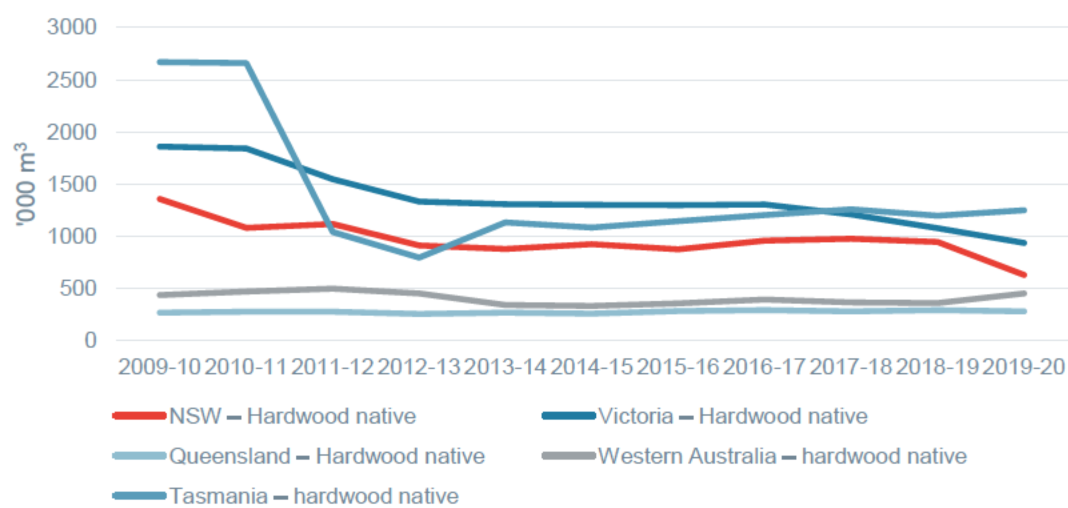
25 Australian Government Rural Industries Research and Development Corporation 2014, *Structural Adjustment in Regional Australia Learning from experience, improving future responses by Aither*, available at: https://www.aither.com.au/wp-content/uploads/2019/04/15-110-NRI-Structural-Adjustment_online.pdf

26 Australian Government Productivity Commission 2001, *Structural Adjustment – Key Policy Issues*, available at: https://www.pc.gov.au/research/completed/structural-adjustment-issues/sakpi.pdf

4.2 Survey of native forest logging structural adjustment packages

According to the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) data for 2019–20, the volume of log removals from Victoria, Western Australia, New South Wales, and Tasmania was 938,000 m^3, 452,000 m^3, 629,000 m^3 and 1,247,000 m^3 respectively. Broadly, hardwood native log harvesting across the States has been flat to declining over the past decade.

Figure 6: Volume of hardwood native logs harvested, by State



Source: Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Australian forest and wood products statistics: March – June quarters 2021.

Note: This data reports on public and private supply volumes.

Victoria and Western Australia are transitioning away from native forest harvesting. In Western Australia logging of native forests will cease by the end of 2023, while Victoria is phasing out native logging of state forests by 2030. In Queensland, state-owned native timber production is being phased out in the south-east, west, and eastern regions, with decisions on the northern region still forthcoming and dependant on plantation supply. Tasmanian structural reform has been ongoing and inconsistent across time, the apparent size of the adjustment in that state potentially providing a source of political and economic rigidity.

We have not included South Australia in our sample as there is no commercial harvesting of native forests in South Australia and there has not been for some time. Native vegetation is protected under the *Native Vegetation Act 1991* and the associated *Native Vegetation Regulations 2017*.[27] Instead, South Australia's forest and wood products industry is entirely plantation-based.

A summary of themes from the structural adjustment packages of other jurisdictions is contained in Box 2.

[27] Australian Government, Government of South Australian 2021, *State Specific Guideline for South Australia*, viewed 17 May 2022, https://www.awe.gov.au/sites/default/files/documents/sa-state-specific-guideline.pdf

Box 2: Lessons in designing native forestry structural adjustment packages

A key theme is signalling the transition out of native forest logging well in advance, in order to provide time for efficient and equitable adjustment. This tended to be coupled with governance arrangements across industry, and negotiations with industry stakeholders as to the most impactful use of structural adjustment funding. In the case of Victoria and Western Australia, governments have materially increased the size of their structural adjustment packages after consulting their stakeholders.

Key and well signalled interventions along the value chain include:

- Policy commitments to support the industry transition through increased investment in plantation resources
- Support for workers through redundancy payments and resources for retraining
- Support for harvesting and haulage contractors and mills though capital redundancy payments, other financial supports and/or contract buy-backs
- Government funding to diversify local regional economies, though details remain unclear.

The basic form of these structural adjustment packages is likely applicable to the NSW public native forestry industry.

Source: Frontier Economics

4.2.1 Selected adjustment assistance in NSW

The NSW Government has in the past has provided structural adjustment support to workers and businesses in the public native hardwood sector. This has been when substantial areas of native timber resource has been protected from logging or when necessary changes have been made to reduce WSA volumes.

For example, in 2010 the NSW Government protected more than 100,000 hectares of river red gum forests in the Riverina-Murray region from logging. The NSW Government's decision reflected recommendations made by the NRC about the conservation and management of the forests, involving estimated industry job losses of approximately 120.[28] The government developed a $97 million structural adjustment package incorporating:[29,30]

- Business exit assistance of $25 million
- Worker assistance to $21.5 million
- Regional Employment and Community Development Fund of $12 million
- National Park funding of $23 million, of which $12 million is capital works.

28 ABC News, *NRC recommends red gum national parks*, viewed 20 April 2022, https://www.abc.net.au/news/2009-12-22/nrc-recommends-red-gum-national-parks/2692286

29 ABC News 2010, *Sartor says red gum compo enough*, viewed 20 May 2022, https://www.abc.net.au/news/2010-05-21/sartor-says-red-gum-compo-enough/835636

30 NSW Parliament 2010, *National Park Estate (Riverina Red Gum Reservations) Bill 2010 (No. 2) Agreement in principle*, viewed 17 May 2022, https://www.parliament.nsw.gov.au/bill/files/357/LA%202210.pdf

This package is similar in design to the more comprehensive structural adjustment packages designed by the Victorian, Western Australian, and Tasmanian public native hardwood sectors.

More targeted financial support has also been provided when necessary reductions have been made to FCNSW's native timber WSAs. For example, the NSW Government provided redundancy payments to workers impacted by a WSA not being renewed (see **Box 3**), and has undertaken a buy back of timber allocations under a WSA (see **Box 4**).

In 2018, the NSW Government also provided a $24 million equity injection to FCNSW to acquire land for new timber plantations.[31]

Box 3: Blue Ridge Hardwoods in Eden

Blue Ridge Hardwoods in Eden had a WSA for 24,000 m^3 of high-quality sawlogs per annum which expired in 2018.[32] The native forest resource was no longer available to supply this quantity of high-quality sawlogs and hence the WSA was not renewed.

FCNSW has been able to offer 25,000 m^3 per annum of smaller regrowth sawlogs rather than high quality sawlogs. Presumably to ensure that it obtains a fair market price for this wood, it was also offered the smaller sawlogs to the market via a competitive tender process.

Blue Ridge Hardwoods would have required new or altered equipment to process the smaller logs. They were unsuccessful in the tender process, which was won by Allied Natural Wood Exports who proposed to build a new mill suited to processing the smaller logs.[33] The government provided financial transition support to the impacted workforce of around 50 employees.[34] A payment of $150,000 was made to each of the 50 employees.

Subsequently, South Coast Timber took over the mill (in October 2020) employing 30 employees (some of whom were retained from Blue Ridge Hardwoods). The mill is sourcing wood supplies from private property and from the Eden Management Area (Forestry).[35]

31 FCNSW 2019, Annual Report 2018–19, p. 11.

32 IPART 2017, *Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report*, December, p. 17.

33 NSW Forestry Corporation, Eden Wood Supply Agreement – statement, viewed 20 April 2022, https://www.forestrycorporation.com.au/about/releases/2019/eden-wsa-statement

34 NSW Parliament, *Budget Estimates 2020–21 supplementary questions Portfolio Committee No.4 – Industry*, viewed 16 September 2022, https://www.parliament.nsw.gov.au/lcdocs/other/15367/Answers%20to%20supplementary%20questions%20-%20Barilaro.pdf

35 Szanto, L 2021, "Future looks bright', Eden's South Coast Timber reflects on first year of business', viewed 20 April 2022, https://www.begadistrictnews.com.au/story/7539230/future-looks-bright-edens-south-coast-timber-reflects-on-first-year-of-business/

Box 4: Boral buy-back of 50,000 m^3 of native timber

In 2014, the NSW Government spent $8.5 million to buy back timber allocations on the north coast from Boral. The purchase reduced Boral's annual supply of high-quality native saw logs by 50,000 cubic metres for nine years to achieve sustainable harvest levels.

The buy back was recommended by a government steering committee which considered it the most effective way of achieving a sustainable yield after investigating North Coast timber supply issues. Boral had in the past sued Forests NSW (predecessor to Forestry Corporation) in 2006 and 2011 for a failure to supply the contracted amount of high-quality timber.

Source: IPART 2017, Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report, December.

4.2.2 Victorian Forestry Plan

In 2019, the Victorian Government announced a 30-year forestry plan to support the native timber industry shift entirely to plantation timber while protecting as many jobs as possible.

The plan includes establishing a Consultative Committee with representatives from industry, VicForests, unions, local councils and government to help manage the transition. In explaining the rationale behind the plan, the Victorian Government notes that, 'since the 1980s the amount of native timber available for harvest has more than halved and is increasingly vulnerable due to the impact of bushfires and environmental protections.' The Victorian Budget Office costed an accelerated version of the plan and found it would substantially improve the state's budget position over the period 2019–20 to 2029–30 (see **Box 5**).

In response to industry feedback, the Victorian Government announced in December 2021 an additional $100 million in transition support, bringing the Government's total commitment to more than $200 million.

The $100 million in newly announced funding included opt-out packages and increased redundancy payments delivering closer alignment with previous forestry industry adjustment packages such as the 2003 Victorian Government Our Forests Our Future assistance and the assistance provided to Tasmanian workers in 2013 by the Commonwealth and Tasmanian Governments.[36,37,38] This funding will also be accompanied by new environmental standards for logging in native forests.[39]

36 Premier of Victoria 2021, Bolstering the Victorian Forestry Plan, https://www.premier.vic.gov.au/bolstering-victorian-forestry-plan (accessed 1 April 2022)

37 Victorian Government, *Victorian Forestry Plan*, viewed 19 May 2022, https://djpr.vic.gov.au/forestry/forestry-plan

38 StarMail, *An increase in support for timber workers through the Victorian Forestry Plan,* viewed 19 May 2022, https://mountainviews.mailcommunity.com.au/news/2021-12-17/an-increase-in-support-for-timber-workers-through-the-victorian-forestry-plan/

39 O'Malley, N 2021, 'New money for transition from old-growth logging in Victoria', *The Sydney Morning Herald*, December 17, available at: https://www.smh.com.au/environment/conservation/new-money-for-transition-from-old-growth-logging-in-victoria-20211217-p59ilv.html

The Victorian Forestry Plan aims to ensure that supply chains and workers relying on native timber can adjust as native forest logging is phased out from 2024 to 2030. Key features of the current plan include support for:[40]

- Mills and harvest haulage contractors: Plant and equipment redundancy payments of up to $250,000 per business, available from 2024, and mill site rehabilitation payments of up to $75,000 available from 2023.
- Mill, harvest, and haulage workers: From 2023, top-up of redundancy payments of up to $120,000, relocation support payments of up to $20,000, per person, and access to training and retraining programs.
- Communities: A $36 million Regional Growth Fund and a $22 million Community Transition and Development Fund to support actions from the local development strategies, particularly targeting job creation that is relevant for the location, timing and skills of affected native timber workers.
- Plantation wood supply: $110 million investment in plantation development 'to leverage and accelerate private investment and boost new plantation development in Gippsland.'[41] New plantations will not be ready for the planned native timber reductions in 2024 or 2030 and are not intended to replace native timber tree-for-tree which has caused concern in industry about job losses.[42]

Under the plan, the industry will hold continued supply of native timber until 2024, after which supply levels will step down until ending in 2030. Between 2024 and 2030, a competitive process will be applied to allocate native timber. In this period mills can enter an 'opt-out scheme' rather than participate in the competitive process for native timber.[43]

40 The Victorian Government 2019, *Victorian Forestry Plan*, accessed 1 April 2022, available at: https://www.vic.gov.au/sites/default/files/2019-11/DJPR-Inclusion-Forestry-Plan-1.pdf

41 The Victorian Government, *Forestry Plantations*, viewed 19 May 2022, https://djpr.vic.gov.au/forestry/plantations

42 Australian Forest Products Association 2021, *Daniel Andrews' sham forestry plan felled,* viewed 19 May 2022, https://ausfpa.com.au/daniel-andrews-sham-forestry-plan-felled/

43 The opt-out scheme provides for redundancy payments for workers of up to $120,000, plant and equipment redundancy payment of up to $250,000, relocation support increased from $20,000 to $45,000 and a doubling of mill site rehabilitation funding from $75,000 to $150,000 among other initiatives. Refer: The Victorian Government, *Victorian Forestry Plan*, viewed 19 May 2022, https://djpr.vic.gov.au/forestry/forestry-plan

Box 5: Estimated budgetary impact of ending native forest logging in Victoria

In 2020, and based on a $120 million transition package, the Victorian Parliamentary Budget Office calculated that an immediate cessation of native forest logging would improve the State's net budgetary position by $192 million.

The Victorian Parliamentary Budget Office was asked to calculate the net position to the State of Victoria from immediately ending native forest logging in Victoria (in contrast to the announced 2030 cessation of native forest logging outlined above) as well as bringing forward the proposed $120 million transition package for industry and workers.

The Parliamentary Budget Office expected such a policy would decrease the State's net position by $15.3 million over three years from the 2019–20 Budget due to:

- Decrease revenue of $31.3 million from the abolition of VicForests
- Decreased operating expenses of $16 million largely from a cessation of grants to VicForests.

Over the period 2019–20 to 2029–30 the State's budgeted net position was expected to improve by $191.9 million due to:

- Decrease in operating expenses of $309.6 million due to cessation of grants to VicForests
- Decrease in revenue of $177.7 million due the abolition of VicForests.

Source: Parliamentary Budget Office 2020, End native forest logging in Victoria, viewed 11 April 2022, https://sway.office.com/cQXoiKWO0HHNL6ml

4.2.3 Western Australia Native Forestry Just Transition Plan

In September 2021, The Western Australian (WA) Government announced that native forest logging will come to an end at the start of 2024[44] – the State's next forest management plan covering the period 2024–2033 would not include native forest clearing.[45] The Native Forestry Transition Group (NFTG) was established to assist in the development and implementation of the plan, consisting of local industry, union, and government stakeholders.

The WA government stated that its decision, 'was driven by the impacts of climate change, the importance of maintaining biodiversity and forest health, the need for carbon capture and storage, and declining timber yields.'[46]

[44] WA Government 2021, McGowan Government's historic move to protect native forests. 8 September. Available at: https://www.mediastatements.wa.gov.au/Pages/McGowan/2021/09/McGowan-Governments-historic-move-to-protect-native-forests.aspx (accessed: 20 May 2022).

[45] From 2024, timber taken from Western Australia's native forests will be limited to forest management activities that improve forest health and clearing for approved mining operations.

[46] The WA Government, *Native Forest Transition*, viewed 4 April 2022, https://www.wa.gov.au/organisation/department-of-jobs-tourism-science-and-innovation/native-forest-transition

Some industry participants criticised an apparent lack of consultation behind this decision[47,48] and some members of the logging sector expressed concern about alternative employment options[49] – it was reported that up to 400 forestry jobs will be lost by the decision to stop native forest harvesting.[50]

Key features of the Western Australia Native Forestry Just Transition Plan include:

- An immediate 12-month freeze on the logging of 'two-tier' karri forests in the South West region which exhibit characteristics of old-growth forest.[51,52]
- A $80 million Native Forest Just Transition Plan which is intended to provide support to affected workers and businesses and drive further diversification of local economies (increased from an initial $50 million).[53]
- $350 million over ten years for the creation of new softwood plantations across the South-West.
- A $26.9 million Business Transition Program to support native timber sawmills and harvesters before native forestry ends in 2024. The Program provides for an Industry Restructure Payment based on contract volumes, further support of up to $225,000 for redundancy payments, site-clean up, and equipment reimbursement, and funding of up to $50,000 for firewood processors who exit the industry.[54]

The Western Australian Government noted a range of existing grants and program available to support industry[55] and its expectation that funds under the Native Forest Just Transition plan would be available in the first half of 2022, such that workers and business can make informed decisions well in advance of December 2023.[56]

47 Zimmerman, J & Law, P 2021, 'Logging of native forests to be banned in WA from the end of 2023', *The West Australian*, 8 September, available at: https://thewest.com.au/politics/state-politics/logging-of-native-forests-to-be-banned-in-wa-from-the-end-of-2023-ng-b881997499z

48 Morton, A 2021, 'Western Australia to ban native forest logging from 2024 in move that blindsides industry', *The Guardian*, 8 September, available at: https://www.theguardian.com/australia-news/2021/sep/08/western-australia-to-ban-native-forest-logging-from-2024-in-move-that-blindsides-industry

49 Shine, R et al. 2021, 'Logging of WA native forests to be banned under state budget plan unveiled by Mark McGowan' *ABC news*, 8 September, available at: https://www.abc.net.au/news/2021-09-08/logging-of-wa-native-forests-to-be-banned-in-state-budget-plan/100443070

50 Zimmerman, J & Law, P 2021, 'Logging of native forests to be banned in WA from the end of 2023', *The West Australian*, 8 September, available at: https://thewest.com.au/politics/state-politics/logging-of-native-forests-to-be-banned-in-wa-from-the-end-of-2023-ng-b881997499z

51 The WA Government, *Protective Western Australia's Native Forests,* viewed 19 May 2022, https://www.wa.gov.au/system/files/2021-09/Announcement%20Fact%20Sheet.pdf

52 Conservation Council of Western Australia 2020, *Ancient Southwest forest spared the chainsaw this year but protection must become permanent,* viewed 19 May 2022, https://www.ccwa.org.au/ancient_southwest_forest_spared

53 WA Department of Jobs, Tourism, Science and Innovation 2022, *$30 million boost to support native forestry transition*, viewed 19 May 2022, available at: https://www.wa.gov.au/government/announcements/30-million-boost-support-native-forestry-transition

54 WA Department of Jobs, Tourism, Science and Innovation 2022, *Business Transition Programs*, viewed 19 May 2022, available at: https://www.wa.gov.au/government/document-collections/business-transition-programs

55 WA Department of Jobs, Tourism, Science and Innovation 2022, *Grants Assistance and Programs Register for WA industry*, viewed 19 May 2022, available at: https://www.wa.gov.au/organisation/department-of-jobs-tourism-science-and-innovation/grants-assistance-and-programs-register-wa-industry

56 WA Department of Jobs, Tourism, Science and Innovation 2022, *Native Forest Transition,* viewed 19 May 2022, available at: https://www.wa.gov.au/organisation/department-of-jobs-tourism-science-and-innovation/native-forest-transition

4.2.4 South-East Queensland Forests Agreement

The South-East Queensland Forests Agreement (SEQFA) was signed by the Queensland Government, the timber industry and the conservation sector in 1999.[57] At the time of signing, the forests of South-East Queensland (SEQ) contributed about 75% of the sawlog volume that was processed in Queensland.[58]

The agreement, and arrangements in other regions, aimed to end timber production in State forests and allow the transition of these areas to the conservation estate. The agreements put in place long-term supply agreements for the supply of State-owned native timber that would phase out in accordance with the following timetable:

- South-East hardwoods region by 31 December 2024
- Eastern hardwoods region by 31 December 2026
- Western hardwoods region in 2034.[59]

No decisions yet have been made regarding other regions of Queensland (covering the rest of the State north of approximately Mackay) with future decisions being informed by outcomes of assessments into sustainable long-term supply options for hardwood and cypress timber.

As part of the South-East transition, the government commenced a native hardwood plantation program in 1999 to support the supply of alternative resources after 2024. An independent review of the hardwood plantation program was completed in 2015. It showed that many of the hardwood plantations established were performing poorly and would not deliver the intended 20,000 ha of hardwood resource.[60] Because of this, the decision was made to end the program[61] and state-owned native timber production in the Eastern hardwoods region was extended by two years, to the end of 2026, to provide time to 'undertake the work needed to make future decisions.'[62]

In the absence of policy certainty supporting the transition out of native forest logging, and an apparent inadequacy of plantation resource, the timber sector has framed the problem as 'becoming an industry crisis' which could deter investment and financing in the timber industry.[63]

57 Queensland Government 2020, *State-owned native timber,* viewed 18 May 2022, available at: https://www.daf.qld.gov.au/business-priorities/forestry/native-timber-action-plan/state-owned-native-timber

58 Queensland Parliamentary Library, July 2000, *Regional Forest Agreements Research Bulletin No 2/00.*

59 Queensland Government 2020, *State-owned native timber,* viewed 18 May 2022, available at: https://www.daf.qld.gov.au/business-priorities/forestry/native-timber-action-plan/state-owned-native-timber

60 At the time planting commenced, large-scale native hardwood plantations were untested in Queensland. Planting locations were challenging to find as available land was typically of marginal soil quality and in areas of increasing climate variability. More suitable land was either already in use for agriculture or was too expensive to buy. Matching the right species to the right site proved challenging, with research benefits from improved plant genetics, including for insect and pest resilience, yet to be realised. Despite the plantations being managed using well-established practices, the site and species selection challenges, along with increasing climate variability, pests and diseases, resulted in poor growth rates and the commercial failure of large areas of plantations.

61 Queensland Government 2020, *Hardwood plantation program,* viewed 20 May 2022, available at https://www.daf.qld.gov.au/business-priorities/forestry/native-timber-action-plan/hardwood-plantation-program

62 Queensland Government 2020, *State-owned native timber,* viewed 18 May 2022, available at: https://www.daf.qld.gov.au/business-priorities/forestry/native-timber-action-plan/state-owned-native-timber

63 Timber Queensland, *Securing the future of South-East Queensland's native hardwood industry,* viewed 20 April 2022, available at: http://www.timberqueensland.com.au/Growing/SEQNativeHardwood.aspx

In June 2021, the Queensland Government has appointed a Native Timber Advisory Panel to advise on policy options and implications for the native timber industry. The Panel met in mid-2021, with a study that is due by the end of 2021[64] – the study is currently not publicly available.

4.2.5 Tasmania and ongoing reform

Sustainable Timber Tasmania (formerly Forestry Tasmania) operates across native forest (87% forest type), hardwood plantation (6.5%) and softwood plantation (6.5%) forest types.[65]

In 2011, Gunns Limited, a major forestry enterprise, decided to exit native forestry. The company withdrew from native forest harvesting, closed sawmills, stopped exporting woodchips and sold the Triabunna woodchip mill[66] to new owners who sought to redevelop the site for tourism.[67] This coincided with the Tasmanian Forests Intergovernmental Agreement, a $277 million agreement between the Commonwealth and the Tasmanian Governments and included: [68]

- $85 million to support logging contractors leave the industry following the decision of Gunns Limited.
- $43 million to protect 430,000 hectares of new reserve[69]
- $120 million over 15 years to fund regional development projects.

Relatedly, participants in the native forestry industry and environmentalists signed the Tasmanian Forest Agreement in 2012[70] which agreed to place 500,000 hectares of native forest in reserves (including 400,000 hectares as soon as legislation was made)[71] while also agreeing that areas of native forest could be logged – the agreement also pledged to eventually end all native forest logging.[72] Tasmania's parliament passed the Tasmanian Forests Agreement putting the agreement into effect in 2013, some key measures (largely funded by the Commonwealth Government) included:[73]

- Economic diversification fund: $120 million to fund regional economic development initiatives, $115 million of which will be funded by the Commonwealth Government.

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64 Coade, M 2021, 'Advisory panel to oversee future of Queensland forest industry', *The Mandarin*, 13 June, available at: https://www.themandarin.com.au/159946-advisory-panel-to-oversee-future-of-queensland-forest-industry/

65 Sustainable Timber Tasmania 2021, Annual Report 2021, p. 86. https://sttwebdata.blob.core.windows.net/stt-prod/assets/Sustainable_Timber_Tasmania_Annual_Report_2021_55b8acc215.pdf

66 ABC news, *Timeline: The rise and fall of Gunns*, viewed 17 May 2022, available at: https://www.abc.net.au/news/2012-09-25/gunns-timber-company-rise-fall-timeline/4235708

67 ABC news, *Triabunna woodchip mill; Timeline of key events*, viewed 17 May 2022, available at: https://www.abc.net.au/news/2015-10-14/triabunna-woodchip-mill-timeline-of-key-events/6823748?nw=0&r=HtmlFragment

68 Australian Government Department of Agriculture, Water and the Environment, *Tasmanian Forests Intergovernmental Agreement*, viewed 17 May 2022, available at: https://www.awe.gov.au/agriculture-land/forestry/national/aus-govt-tas-forests

69 Australian Government Department of Agriculture, Water and the Environment, *Conservation Agreement to protect interim forest area under the Tasmanian Forests Intergovernmental Agreement*, viewed 19 May 2022, available at: https://www.awe.gov.au/agriculture-land/land/forests/intergovernmental-agreement/conservation-agreement

70 Tasmanian Forests Agreement 2012, available at: https://www.wilderness.org.au/images/resources/Tasmanian-Forest-Agreement-2012.pdf

71 Wilderness Society 2018, *The Tasmanian Forest Agreement: your questions answered*, viewed 19 May 2022, available at: https://www.wilderness.org.au/news-events/the-tasmanian-forest-agreement-your-questions-answered

72 ABC news 2010, *Native logging end to take decades*, viewed 19 May 2022, available at: https://www.abc.net.au/news/2010-10-19/native-logging-end-to-take-decades/2304032

73 Parliament of Tasmania 2013, *Report on the Tasmanian Forests Agreement Bill 2012,* available at: https://www.parliament.tas.gov.au/ctee/Council/Reports/TFA%20FINAL%20REPORT.pdf

- Worker support: $45 million in transition support payments to workers directly impacted, and $25 million to provide immediate employment and training support for redundant workers.
- Business support: $45 million for native forest harvest and haulage contractors exiting the industry, $10 million for sawmills, and $20 million to assist employees and contractors that might be affected by sawmill exits.
- Sawlog contract buybacks of $15 million.
- Manufacturing Innovation Development: $22.6 million to assist industry to transition to greater use of plantation timber in the longer term.

In 2014, a new Tasmanian Government repealed the Tasmanian Forest Agreement Act and reclassified 400,000 hectares of native forest for potential future logging after a six-year moratorium.[74,75]

There is evidence that native forest logging in Tasmania is not financially sustainable – based on publicly available information cash operating surpluses and profitability appear to be reliant on Government funding (which contributes toward the performance of Community Service Obligations). In 2021, Sustainable Timber Tasmania reported a net profit after tax of $2.7 million, from revenues of $125 million ($12 million of which was government finding).[76] The financial performance of Sustainable Timber Tasmania has been under scrutiny for some time, with some estimates in the media revealing structural operating deficits and a reliance on government subsidy since 2004.[77]

In early 2022, Birdlife Australia proposed that legislative requirements on Sustainable Timber Tasmania be lifted such that it is not required to make 137,000 m^3 of native forest timber available each year – therefore allowing the protection of Swift parrot habitat (the parrot could be extinct by 2031 in a scenario of continued logging).[78,79] The proposal is consistent with a request by Sustainable Timber Tasmania's own Board (then Forestry Tasmania) in 2016 which found the legislated requirement forced it to lose money.[80] The Tasmanian Government has not publicly responded to the proposal.

74 Ikin, S & Nightingale, T 2014, 'Tasmania repeals the forestry peace deal between conservationists and loggers, opening up 400,000 hectares', ABC news, 2 September, available at: https://www.abc.net.au/news/2014-09-02/forestry-peace-deal-repeal-bill-passed-by-tasmania-parliament/5714634

75 The Conversation *End of Tasmania's forest peace deal heralds more* uncertainty viewed 19 May 2022 available at: https://theconversation.com/end-of-tasmanias-forest-peace-deal-heralds-more-uncertainty-31010

76 Sustainable Timber Tasmania, Annual Report 2021, p. 33, https://sttwebdata.blob.core.windows.net/stt-prod/assets/Sustainable_Timber_Tasmania_Annual_Report_2021_55b8acc215.pdf

77 Lawrence, J 2018, 'Tasmanian regional forest agreement delivers $1.3bn losses in 'giant fraud' on taxpayers', *The Guardian*, 29 March, available at: https://www.theguardian.com/environment/2018/mar/29/tasmanian-forest-agreement-delivers-13bn-losses-in-giant-on-taxpayers

78 The Tree Projects, *The Swift Parrot Protection Plan*, viewed 20 April 2022, available at: https://www.thetreeprojects.com/swiftparrot

79 Morton, A 2020, 'Tasmania's 'precious' swift parrot habitats marked for logging despite expert warnings', *the Guardian*, 11 June, available at: https://www.theguardian.com/environment/2020/jul/11/tasmanias-precious-swift-parrot-habitats-marked-for-logging-despite-expert-warnings

80 Humphries, A, 'new plan could save swift parrot from 'imminent danger of extinction', researchers say', *ABC news*, 22 February, available at: https://www.abc.net.au/news/2022-02-22/swift-parrot-forestry-extinction-tasmania/100849384

5 NSW structural adjustment package

5.1 Possible features of NSW package

The design of a possible structural adjustment package to transition the NSW public forestry industry out of native forest logging should be:

- Targeted to impacted businesses, workers, and communities
- Proportionate to participants' economic and financial exposures to native forest logging
- Relevant to addressing clearly identified and temporary business disruption, economic exposure, and equity concerns.

Adherence to these principles in the design of a structural adjustment package will provide some assurance that the package negotiated with stakeholders will deliver efficient, equitable, and cost-effective outcomes.

In accordance with these principles, structural adjustment assistance is targeted to the primary processing sector of the native hardwood supply chain receiving wood supply from FCNSW. The elements of the assistance package have been estimated to include:

- Business support payments for harvesters, haulers, and mills to support redundancies and retraining, business repurposing, or the write-down of assets
- The buying out or phasing down of WSAs with mills
- Where relevant, economic diversification packages for those local regions most impacted by a cessation of native forest logging.

Separate to the transition support payments, the potential cost of establishing new plantations to provide additional local wood supply in the medium to long term is also investigated. Plantation establishment costs have been assessed separately from the elements of the package that involve direct support payments and grants from government.

The decision to invest in plantations needs to be undertaken on a commercial basis with an expert understanding of plantation establishment and management costs, how best to meet expected timber product demand, and with an understanding of expected long term financial returns. Therefore, it is assumed that this investment would be made by FCNSW (and potentially other businesses) and hence would be off-budget.

Finally, it is assumed that the transition out of public native forestry would only occur, and the adjustment package implemented, from 2028-29 once the majority of the current WSAs with processors have expired (assuming that there are no further WSA renewals beyond the recent five-year extension of the North Coast WSAs)[81].

[81] https://www.nsw.gov.au/media-releases/wood-supply-agreements accessed 4 August 2022.

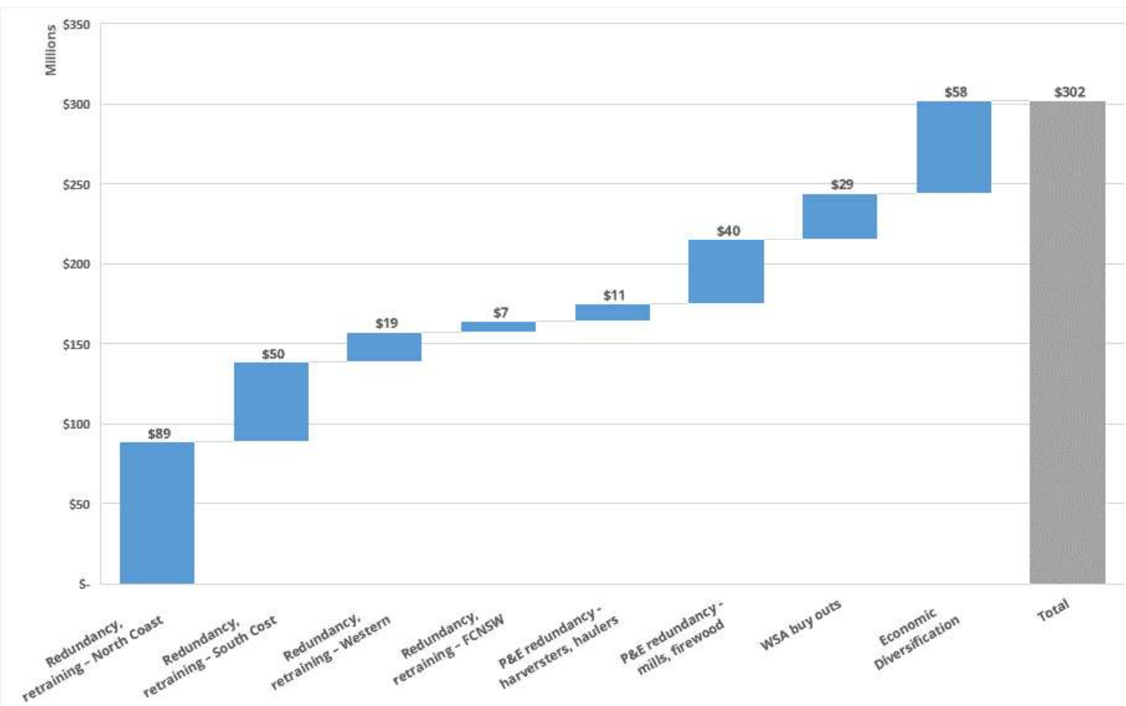
5.2 Cost estimate for structural adjustment support

We have estimated the potential costs to the NSW government associated with a structural adjustment package. Costs have been benchmarked against announced policy costs in comparable jurisdictions were available, and where relevant, on historic sector-specific adjustment payments made in NSW. The estimated costs should be interpreted as conservative and indicative.

We estimate that a structural adjustment package to end FCNSW's native forest logging could cost in the order of **$302 million** (noting that this does not include plantation establishment costs which are considered separately). This includes the cost of worker redundancy and retraining, plant and equipment redundancies, WSA buyouts, and funding for economic diversification packages. The $302 million compares to the more than $90 million recently announced in Victoria and $80 million in WA (excluding plantation expansion). The costs are higher for NSW given the larger size of the public native sector relative to Victoria and WA.

Figure 7 provides a summary of how the cost estimate for a structural adjustment package to transition out of public native forest logging has been built up. **Table 3** provides a detailed breakdown of these first pass estimates of costs.

Figure 7: Estimated costs to end NSW public native forest logging



Source: Frontier Economics analysis

Table 3: Benchmarking structural adjustment costs

Intervention	Scale assumptions	Payments	Cost Estimate
Redundancy and retraining support for workers – North Coast	590 direct employees (Harvest/haulage and mills, consistent with NRC estimate)	$150,000 per worker (as per Blue Ridge Hardwoods)	$89 million
Redundancy and retraining support for workers – South Coast	332 direct employees, (Harvest/haulage and mills, consistent with NRC estimate)	As above	$50 million
Redundancy and retraining support for workers – Western	126 direct employees calculated proportional to WSA volumes	As above	$19 million
Redundancy and retraining support for impacted FCNSW staff	Estimated 47 employees in the Hardwood marketing and timber sales, and Timber harvesting and roading operations	As above	$7 million [1]
Plant and equipment redundancy (harvesters and haulers)	33 harvesters, 10 haulers, payments capped	$250,000 per firm (as per Victoria)	$11 million
Plant and equipment redundancy (mills)	156 mills in the North Coast and South Coast regions, 3 mills and 8 firewood producers in the Western region	$250,000 per firm (as per Victoria) or $50,000 per firewood producer (as per Western Australia)	$40 million
WSA buyout	Buyout of WSAs that extend beyond 2028 [2]	$19/m^3 per year (as per Boral contract buyback)	$29 million
Regional economic diversification package	Notional, requiring further analysis	As per Victoria	$58 million
Total		Not adjusted for time value of money	**$302 million**

*Source: Frontier Economics analysis. More detail on the data sources regarding employment levels and number of harvesting and haulage contractors and mills is provided in **Appendix A and B**.*

1. To be conservative it is assumed that the FCNSW staff are not included in the direct employment estimates in each region.

2. Includes three Coastal WSAs and one Western WSA.

In terms of the scope of the assistance package, the estimated structural adjustment package, in common with those made elsewhere, focuses most heavily on the directly impacted employees and businesses. This includes those in FCNSW, harvest and haulage contractors and wood processors. Downstream businesses such as manufacturers and retailers are not included in the support package as these sectors will be able to access alternative timber supplies and products that mean they will not be substantially impacted by a formal cessation in native forest logging by

FCNSW. However, the package does include broad based financial support for impacted regional communities.

In June 2022 the NSW Government announced a five-year extension to the North Coast WSAs, most of which were due to end in 2023 while others run through to 2028.[82] The cost of the WSA buyouts is based on buying out those extending beyond 2028. FCNSW has WSAs in the South Coast region that extend beyond 2028 (see details in **Table 9** in **Appendix B**). These are the two ANWE contracts (25,000 m^3 pa. sawlog to 2029 and 290,000 m^3 pa. pulp log to 2033) and the Ryan & McNulty high quality sawlog contract (18,500 m^3 to 2030). In the Western Region, FCNSW has one WSAs that extends beyond 2028 (see details in **Table 10** in **Appendix B)**. This is the Arbuthnot Sawmills contract (4,613 m^3 logs to 30 June 2030).

It is challenging to sensibly estimate costs associated with regional economic diversification and industry development support. The first pass estimate of $58 million is consistent with the Victorian Forestry Plan (that is, $36 million in the Regional Development Growth Fund and $22 million in the recently announced Community Transition Fund).

The NSW government may consider establishing a fund to support actions from local development strategies, particularly targeting job creation that is relevant for the location, timing and skills of affected native timber workers. Any actual costs would necessarily reflect the opportunities, challenges and features of each unique regional economy. Existing regional economic development strategies could guide this initiative, as may existing programs such as the NSW Government's Forest Industries Innovation Fund or the Regional Growth Fund.[83,84]

5.3 Plantation expansion

A final element of the transition may involve prudent investment in plantation expansion in NSW. The sector would sensibly lead this expansion based on its understanding of the best locations, appropriate size of expansion, plantation species and market needs.

An initial estimate of the new plantation establishment cost has been made assuming that there is a 33,000 hectare (ha) plantation expansion. This is the size of the planned expansion in Western Australia and is close to the size of the FCNSW's current hardwood plantation estate, which is just under 35,000 ha.[85]

To estimate the cost of the expansion we have considered plantation establishment costs published by ABARES and by Western Australia as part of their transition package.

Table 4 shows new plantation and establishment costs published by ABARES. ABARES also assume that the land cost for new plantations is approximately $2,900 per ha.

82 NSW Government, Certainty for local timber processors after extension to Wood Supply Agreements, viewed 26 July 2022, https://www.nsw.gov.au/media-releases/wood-supply-agreements

83 In 2018, the NSW Government assisted local council to develop regional economic development strategies. NSW Government 2018, *Regional Economic Development Strategies,* viewed 18 May 2022, available at: https://www.nsw.gov.au/regional-nsw/regional-economic-development-strategies

84 NSW Department of Primary Industries, Forest Industries Innovation Fund, viewed 18 May 2022, available at: https://www.dpi.nsw.gov.au/forestry/forest-industries-innovation-fund#:~:text=The%20NSW%20Government%20is%20committed new%20markets%20for%20forest%20products.

85 FCNSW, 2020-21 Sustainability Report, p. 7.

Table 4: New plantation and maintenance costs

Regime	Establishment ($/ha)	First year ($/ha)	Ongoing ($/ha)	Rotation length (years)
Softwood				
Radiata pine	1,900	482	82	30
Maritime pine	1,900	482	82	40
Caribbean pine	1,900	482	82	30
Southern Pines	1,500	640	90	30
Hardwood				
Tasmanian blue gum–long rotation	2,100	140	180	25
Tasmanian blue gum–short rotation	2,100	140	25	10
Spotted gum (sawlogs)	2,100	140	180	25
Shining gum (pulplogs)	2,100	140	25	10

Source: Whittle, L, Lock, P & Hug, B 2019, Economic potential for new plantation establishment in Australia: outlook to 2050, ABARES research report, Canberra, February, p. 17.

Using the cost assumptions for Radiata pine[86] to estimate a softwood only plantation expansion, the upfront land and establishment cost would be $158 million and the whole of life costs for the plantation (over 30 years, assuming a 7% discount rate) would be NPV$204 million.

Using the cost assumptions for long rotation gum to estimate a hardwood only plantation expansion, the upfront land and establishment cost would be $165 million and the whole of life costs for the plantation (over 25 years, assuming a 7% discount rate) would be NPV$233 million.

This estimate compares to the Western Australian Native Forestry Just Transition Plan which provides a cost estimate of $350 million to provide 'at least an additional 33,000 hectares of softwood timber plantation.'[87] Detailed information is not available to understand what is driving this higher cost estimate for the comparable hectares of new plantation in Western Australia.

We also note that Victorian Plan proposes a $110 million investment in plantation development, though it is not clear how many hectares this is intended to supply.

It is possible that the NSW government may contribute funding to expanding the plantations in NSW. However, this would need to be determined at a later date, and with a better understanding of whether there was a justifiable requirement for government funding.

86 The FCNSW 2020-21 Sustainability Report indicates that Radiata pine accounts for the greatest proportion of FCNSW's softwood plantation species (see p. 7).

87 Forest Products Commission 2021, *premier announces softwood investment*, viewed 18 may 2022, available at: https://www.wa.gov.au/government/announcements/premier-announces-softwood-investment#:~:text=The%20Forest%20Products%20Commission%20(FPC Australia's%20softwood%20plantation%20timber%20industry.

5.4 NSW budgetary impact

Budget impact is deteriorating

Estimating the likely budgetary impact of ceasing FCNSW's native forestry business is more difficult given the limited information available on the true financial position and financial support given to FCNSW's hardwood business and the hardwood sector more generally.

However, it is clear that this budgetary position has been deteriorating significantly since the 2019-20 bushfires. For example, due to the bushfires FCNSW will not be in a position to pay a dividend for the next three years and the NSW Government has offered over $67 million in assistance, much of which is going to the hardwood sector (see details in **Box 6** below).

Box 6: Bushfire related payments and support being provided to the NSW timber industry

- FCNSW's 2021-22 Statement of Corporate Intent report that FCNSW will not be paying a dividend up to and including 2024-25 financial year, due to the impact of the 2019-20 bushfires.
- $41.8 million in approved Bushfire Industry Recovery Package sector development grants.
- $10 million for haulage of fire-affected timber and $15 million for storage assistance (with complementary Commonwealth assistance). NSW successfully negotiated a one-year extension with the Commonwealth for haulage subsidy claims (now expiring June 2022).
- Low interest loans from the Forest Industries Innovation Fund (including a recent increase in the loan cap from $3 million to $5 million).

Source: FCNSW, Statement of Corporate Intent – 2021-22, p. 6, https://www.parliament.nsw.gov.au/lcdocs/other/16422/Answers%20to%20supp%20questions%20-%20Regional%20NSW,%20Paul%20Toole,%20MP%20-%20Received%201%20December%202021.pdf

Understanding the budget impact

Table 5 explores the sources of positive and negative budgetary impacts that could arise by ceasing FCNSW's native forestry business. As shown, there are likely to be substantial budget position improvements, and these are likely to outweigh the budget position reductions.

Table 5: Positive and negative budget impacts

Budget position improvements	Comment	Budget position reductions	Comment
FCNSW Dividend	Improved profitability would increase FCNSW dividend over time (by avoiding the loss making activities of the hardwood division as noted by IPART)	One-off structural adjustment package	Approximately NPV$291 million over 10 years from 2028-29. [4]
Ongoing and one off industry support	Avoided regular structural adjustment and event related payments. Since 2010 this has conservatively been around $180 million to the hardwood sector (excluding FCNSW). [1]	Native forest management costs	These costs would come on-budget through a transfer of responsibility from FCNSW to the NSW National Parks and Wildlife Service. However, these could reasonably be assumed to be equivalent under FCNSW or national parks management.
Avoided CSO payments and other equity injections to FCNSW	The CSO payments alone have been approximately $17 million per annum over the last 7 years. This would amount to NPV$160 million over 10 years. [2] Recent examples of one-off support from the NSW Government includes $105 million in the form of stimulus, equity and dividend relief. [3]		
Forest -related revenue sources	A range of revenue streams associated with the native forests would also come on-budget including park fees, lease revenue, carbon-credit earnings, etc.		

Notes:
1. This includes the 2010 red gum structural adjustment package, the Boral WSA buy out, recent assistance to Blue Ridge Hardwoods workers, and recent bushfire related assistance to the sector (other than to FCNSW).
2. The avoided CSO cost of NPV$160 million reflects approximately $20 million per annum between 2028-29 and 2038-39 (historic costs escalated by 1.4% per annum out to 2038-39 in line with historic trends).
3. FCNSW, 2020-21 Sustainability Report, p.5.
4. The one-off $291 million present value reflects immediate expenditure of $244 million in 2028-29 toward redundancies and WSA buy-outs plus a $47 million present value of ongoing economic diversification funding from 2028-29.

Estimated budget impact

As shown in **Table 5**, we can assume costs are incurred over the 10-year period from 2028-29 and that the impact of a one-off structural adjustment package to the budget position could be in the order of NPV$291 million,[88] reflecting:

- Structural adjustment funding of $244 million, (assumed to be incurred at the beginning of 2022-23) to support worker redundancies and retraining, capital redundancies and WSA buy-backs
- Structural adjustment funding related to regional economic diversification of $6 million per annum for 10 years to 2031–32. This sums to NPV $47 million.

It is assumed that the cost associated with any expansion of the softwood plantation estate would be funded on a commercial basis by FCNSW and hence is assumed to be off budget.

As shown above, under a set of plausible assumptions the $291 million would likely be outweighed by a range of positive budget impacts including avoided ongoing structural adjustment and bushfire support to the hardwood sector, avoided equity injections to FCNSW and the likelihood of increased dividends from FCNSW over time by avoiding the loss making activities of the hardwood division which have been highlighted by IPART.

It is recommended that NSW Treasury undertake more detailed analysis of the budgetary impacts given that it will have access to more detailed budgetary data than is available in the public domain. Wider impacts outside of the NSW Government's net operating position could also be considered including the wider natural capital benefits provided by NSW's native forests to the economy, including carbon, environmental, water production, tourism and mental health benefits.

5.5 Alternative employment opportunities for native forestry workforce

There are likely to be alternative employment opportunities for displaced workers from the native forestry sectors. There will be alternative forms of employment that are associated with the native hardwood forests and softwood plantation forests in the areas. In addition, it is likely that some workers would transition to employment in other sectors of the local economies.

Key areas of significant employment associated with forestry include:

- Forest management: Forest management employees would still be required in the absence of native forest logging, albeit with different management objectives.
- Recreation and tourism: It would be expected that there would be jobs created in recreation and tourism. By means of an illustrative example, Derby in the North East of Tasmania has created around 100 part-time and full-time jobs as result of becoming a mountain biking destination,[89] while the Wild Mersey mountain bike development in the north west of Tasmania is estimated to create 51 full-time jobs.[90] This analysis included development of a network of mountain bike trails to become a tourism destination and therefore 50-100

88 That is, the impact of the structural adjustment package discounted to 2028-29 from across the 2028-29 – 2037-38 period. Assumes a 4% discount rate.

89 Australian Geographic, *Going with the flow down Derby way.*

90 Mountain Bike Australia, *The Rise of Blue Derby Case Study*, viewed 8 September 2021, available at: https://www.mtba.org.au/wp-content/uploads/CCJ17427-Blue-Derby-Case-Study.pdf

recreation and tourism jobs supported may be a reasonable benchmark. Additional information is provided in **Box 7**.

- Plantation-based forestry work: both in softwood and hardwood plantations and in the establishment and management of new plantations, for which there is known demand associated such as with the Visy paper mill in Tumut.[91] Softwood plantation work in the area – in the Eden RFA region, the softwood sector centres around the Snowy Monaro LGA. In the Southern RFA region, the softwood industry is concentrated around Tumut which is within the Snowy Valleys LGA.[92] Furter north the softwood industry has employment concentrations in Oberon LGA and Walcha LGA.[93]
- Fire and invasive species management: Harvesting and haulage contractors have already diversified in providing firefighting and fire management services in the forests. There are also increasing opportunities in invasive species management (e.g., control of feral deer). It should be noted that the harvesting and haulage contractors may also work over significant areas across NSW and including into Victoria.
- Management of carbon and biodiversity credits: The climate benefits of the carbon stored in plantations offer a potential new income stream for plantation forestry and potentially the incentivisation of smaller scale farm forestry, with associated job creation and the opportunity for co-benefits including biodiversity credits.[94]

Box 7: Mountain bike trail industry in Tasmania and New Zealand

Derby in north-east Tasmania is an example of a rural town which has been transformed by developing a network of high quality mountain bike trails. Around 30km of purpose built mountain trails were opened in 2015 with the network now extending to more than 80km. Prior to covid the trails were getting 30,000 visitors per year, bringing an estimated $30m per annum of tourism spend while it has been reported that the network cost $3.1m to develop. It has been estimated that the area supports around 100 jobs (a combination of full-time and part-time roles).

In Rotorua, New Zealand they have 180km mountain bike trail network. This has been estimated to bring between NZ$29.2 million and NZ$47.4 million per annum and support up to 340 jobs.

Source: Australian Geographic, Going with the flow down Derby way; Mountain Bike Australia, The Rise of Blue Derby Case Study; Stuff NZ, How mountain biking became part of Rotorua's DNA.

91 Hawkins, D. 2020, Submission by Visy Pulp and Paper Pty Ltd (Visy) to the House of Representative Standing Committee on Agriculture and Water Resources Timber Supply Chain Constraints in the Australian Plantation Sector. Commonwealth of Australia, Canberra.

92 NSW Department of Primary Industries 2018, *NSW Regional Forest Agreements – Assessment of matters pertaining to renewal of NSW Regional Forest Agreements*, August p. 299.

93 NSW Department of Primary Industries 2018, *NSW Regional Forest Agreements – Assessment of matters pertaining to renewal of NSW Regional Forest Agreements*, August p. 299.

94 Parliament of the Commonwealth of Australia 2021, 'Aussie logs for Aussie jobs', available at: https://parlinfo.aph.gov.au/parlInfo/download/committees/reportrep/024630/toc_pdf/AussielogsforAussiejobs.pdf fileType=application%2Fpdf

A FCNSW native forestry business

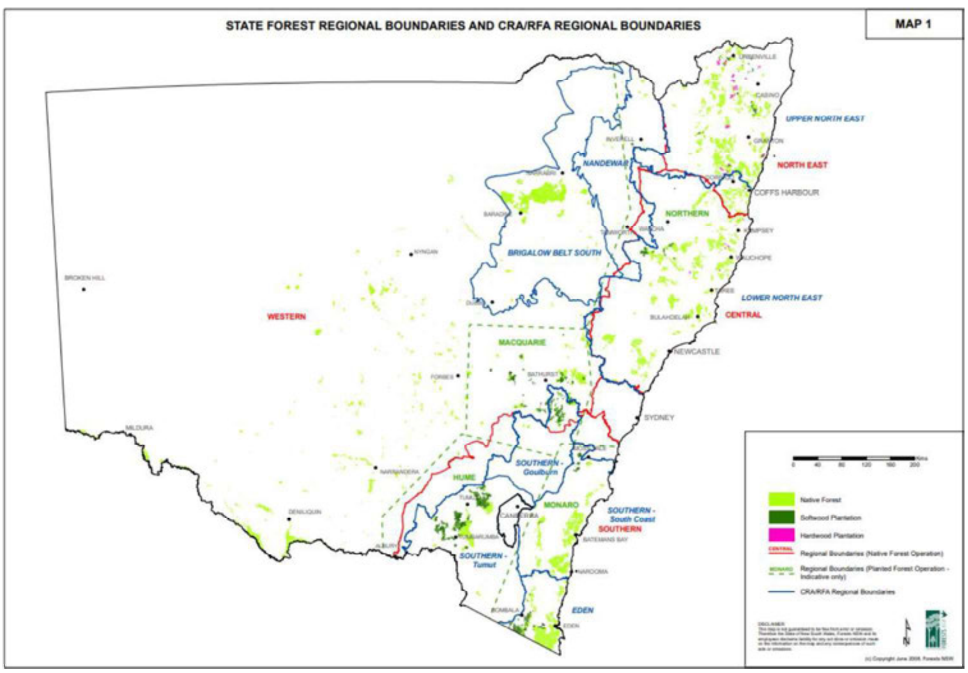
This attachment provides an overview of the FCNSW's native forestry business including the size of the native forest estate, the log products and volumes that it supplies, the financial position of the hardwood business and the approximate number of employees in the hardwood business.

FCNSW native forest estate

The native hardwood forests in NSW are an important natural resource, providing a range of economic and environmental services. FCNSW manages approximately two million hectares of native forests and 34,000 hectares of hardwood plantations in the north[95]. Around half of this area is managed for conservation and the other half is able to be harvested.[96]

Figure 8 shows the areas of native forest resource managed by FCNSW. The majority of the native forest timber is harvested from the three Regional Forest Agreements (RFAs) areas in NSW, which are the North East, Southern and Eden RFA areas.[97]

Figure 8: State Forest and Regional Forest Agreement Boundaries



Source: FCNSW, Boundary Map, https://www.forestrycorporation.com.au/operations/esfm (accessed 24 March 2022).

95 FCNSW, *Statement of Corporate Intent – 2021-22*, p. 4.

96 FCNSW, *Impact of fires 2019–20,* viewed 20 April 2022, https://www.forestrycorporation.com.au/operations/fire-management/fire-impact-of-2019-20

97 The RFAs between the Australian Government and the NSW government control and manage the native forests in these areas and seek to balance economic uses with environmental protections.

FCNSW native forest log supply

FCNSW grades the native timber logs it harvests according to their size, shape and quality and sells them as 'high quality' and 'low-quality' log products. The classification of the log products and the processed wood products produced from them are shown in **Table 6**.

Hardwood processors in NSW currently source the majority of their wood supply from FCNSW, with a smaller volumes sourced from private native forests.

Table 6: Native forest log products and use

Log product type	Processed wood product
High quality	
Poles and piles	Power poles
Girders	Construction beams
High quality sawlogs	Flooring and decking
Low quality	
Low quality sawlogs	Fencing pales
Pulpwood	Woodchips (for paper)
Firewood/other	Firewood

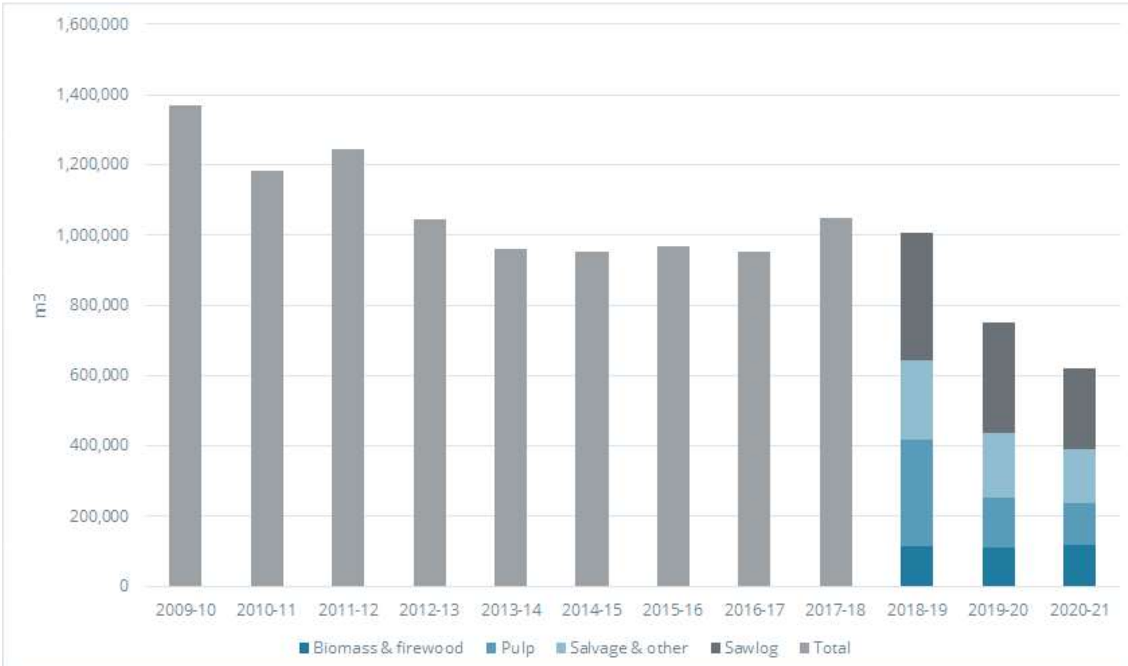
Source: IPART 2017, Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report, December, p. 14

While over 50 species of native timber is harvested, five species contribute the majority of FCNSW's revenue. This includes Blackbutt, Spotted Gum, Brush Box, Blue Gum and Tallowwood. Total hardwood timber harvested by FCNSW is shown in **Figure 9**. This include native timber and hardwood plantation timber harvested and shows that total hardwood timber production has fallen from just under 1.4 million cubic meters (m3) in 2009-10, to just over 0.6 million m3 in 2020-21.

Hardwood plantation volumes as a proportion of total hardwood sales shows significant variation in the data reported in FCNSW's 2021 Sustainability Report. Over the period from 2010-11 to 2020-21 it varies between 4% and 40% of hardwood sales from year to year.[98]

98 FCNSW, *Sustainability Report 2020–21*, p.9.

Figure 9: FCNSW hardwood timber harvested



Source: FCNSW Sustainability Reports

Note: The breakdown by product is only published from 2018-29 to 2020-21

FCNSW's ability to supply hardwood has been substantially reduced by the 2019-20 bushfires

FCNSW conducted a preliminary assessment of the impact of the 2019-20 bushfires on long term sustainable yield in 2020.[99] More recently, the NSW Natural Resources Commission (NRC) has prepared a detailed report for the NSW Government on the short and longer terms impacts of the bushfires on FCNSW's native timber supplies.[100]

The analysis by FCNSW in 2020 found that:

- In the North East RFA area:
  - Around 60% of the net harvestable area available for timber production was impacted by fires in the Upper North East and 38% in the Lower North East, or close to 50% of the net harvestable area across the region
  - Over 10% of the hardwood plantation estate was affected
  - Blackbutt log supply can be maintained but the Spotted Gum on the North Coast (which grows significantly slower than Blackbutt) was heavily affected by fire
  - Long-term sustainable timber supply from the North East forests was estimated to have fallen by approximately 4%.
- In South Coast and Eden RFA areas:

99 The sustainable yield is intended to show the amount and types of log products that can be harvested from the native forest each year without diminishing the volume the forests can produce into the future. FCNSW 2020, *2019–20 Wildfires NSW Coastal Hardwood Forests Sustainable Yield Review*, December.

100 NSW Natural Resources Commission 2021, *Coastal IFOA operations post 2019/20 wildfires*, June. This was a Cabinet-in-Confidence report that has been publicly leaked.

- Over 80% of the forest area that is able to be harvested in the South Coast and Eden RFA areas were impacted by fire
- The biggest impacts were in the southern regions, with lowered sawlog availability in the South Coast and Tumut regions
- The recovery of the forests in these areas will take longer than the northern NSW forests as the southern region forests are slower growing
- Long-term sustainable timber supply from the south coast forests was estimated to have fallen by approximately 30%.

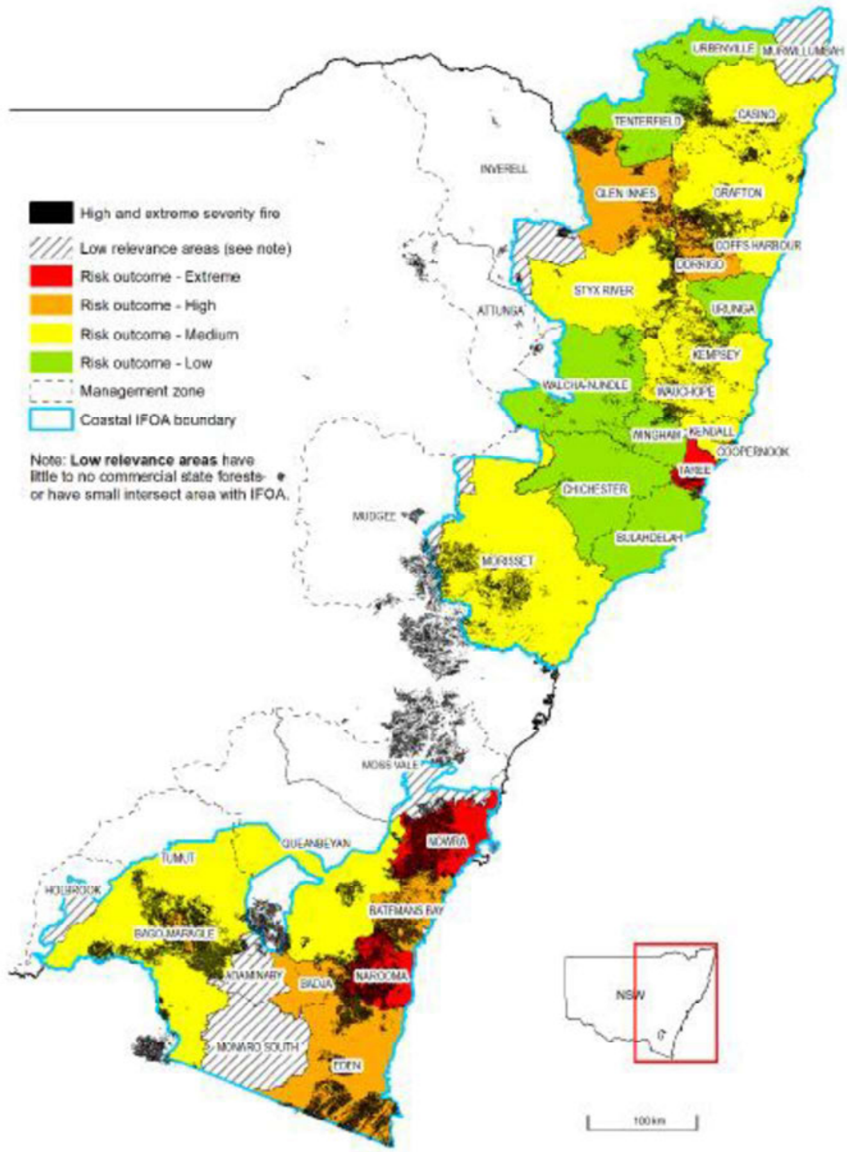
The more recent analysis by the NRC has found the following in terms of bushfire impacts:

> *Impacts were most severe in the South Coast subregion, where there may be up to an 80-90 percent reduction in planned wood supply volume based on the Commission's recommended pathways and risk mitigations. In the Eden subregion, risk mitigations are expected to reduce available wood supply volume by 40 percent. These impacts, while not as large as in the South Coast subregion, are still significant. In the Tumut subregion there is an estimated reduction in supply of approximately 35 percent of wood supply agreement volume. Across the north coast subregions, wood supply may be reduced by 10-20 percent under the recommended pathways and risk mitigations.*

This suggests a more significant impact on wood supply than the initial analysis by FCNSW.

As a result, the NRC has recommended that harvesting be suspended for three years from February 2020 in three management zones shown in red in **Figure 10** (Narooma, Nowra and Taree). Restricted harvesting arrangements have also been recommended in a further 17 management zones across the Southern, Eden and North East RFA areas. This is the areas marked in orange and yellow in **Figure 10**.

Figure 10: NRC risk assessment results by management zone



Source: NRC 2021, Advice on Coastal IFOA operations post-2019-20 wildfires, Final Report, June, p. 5.

Limited or negative returns earned by the hardwood business

It appears that the FCNSW (a government owned entity) receives very limited financial returns on the harvesting and sale of native hardwood forests. Financial data relating to the native forest business alone or individual RFA regions is not publicly available.

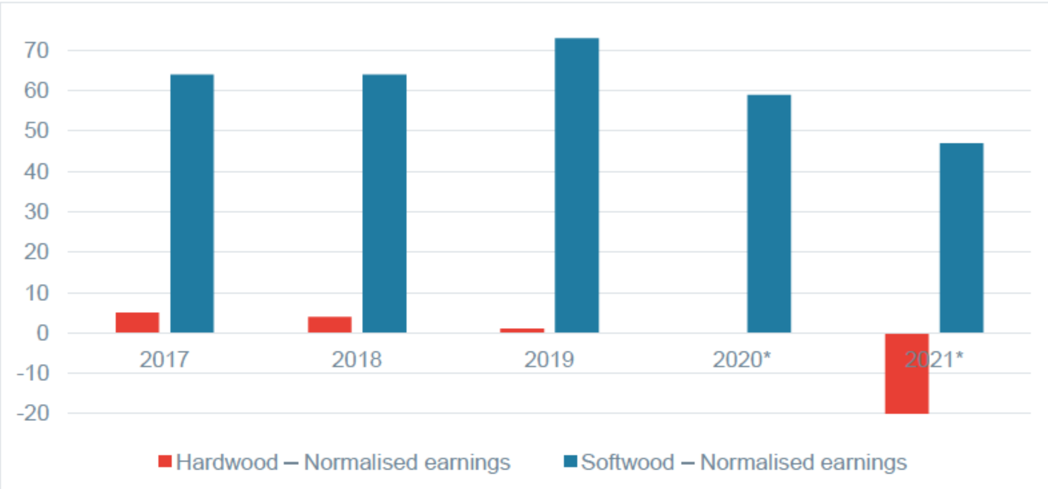
Financial information is published on FCNSW's hardwood division, which includes both native forest harvesting and hardwood plantation sales.

Figure 11 provides a timeseries of normalised earnings for the FCNSW's hardwood and softwood divisions. FCNSW's hardwood division made normalised earnings of -$6 million in 2021, declining to -$20 million if fire-recovery expenses are included. Average normalised earnings across 2017–

2021 were $2.2 million per annum in contrast to $66 million per annum for the softwood division (excluding fire-recovery expenses).[101]

This poor normalised earnings return does not consider the debt that it is servicing, and it appears unlikely that the hardwood division would meet a commercial target return on capital employed. Greater transparency is needed in NSW about the financial position of the native forest business to support informed policymaking.

Figure 11: FCNW normalised earnings: Hardwood and softwood divisions



Source: FCNSW, Annual Report 2012-13 to 2020-2021; Frontier Economics analysis.

Note: Figures include fire-recovery expenses for hardwood ($7M in 2020; $14M in 2021) and softwood ($8M in 2020; $15M in 2021) divisions.

FCNSW acknowledges in its 2021 Sustainability Report that reductions in total revenue was predominately due to a reduction in hardwood revenue, resulting from reduced operations in fire-affected areas as well as significant wet weather and flooding on the north coast. The FCNSW does not expect financial performance to recover for 'several years' as a consequence of these factors.[102]

In terms of FCNSW's overall business, the hardwood division accounts for a much smaller proportion of timber volumes and revenue. In 2020-21, FCNSW's softwood volumes harvested were close to 5 million m3 compared to just over 0.6 million m3 for hardwood. In terms of revenue, in 2020-21 hardwood sales revenue was $89 million and softwood sales revenue was $300 million.[103]

IPART's analysis indicates that the hardwood business is not covering costs

IPART has responsibilities to review, benchmark and report on FCNSW's native timber harvesting and haulage costs. In its two reports to date, IPART has raised concerns that FCNSW is not recovering the costs of its native timber sales.

101 FCNSW, *Annual Report 2020–21*, p. 11, 13.

102 FCNSW, *Sustainability Report 2020–21*, p. 5.

103 FCNSW, *Sustainability Report 2020–21*, p.10.

For example, IPART's 2017 report states:

> *FCNSW's native timber business incurs significant direct costs in managing forests to harvest native timber. These costs include developing harvesting plans, tree selection and marking, building roads to access coupes for harvesting, forest re-generation, and complying with environmental laws.*
>
> *Our consultations and analysis of FCNSW data indicate the current stumpage prices FCNSW charges are unlikely to recover these direct costs in some harvest areas, particularly the New England area. As a result, its harvesting activities in these areas may be loss-making for FCNSW.*
>
> *FCNSW's delivery charge is under-recovering its harvesting and haulage costs (including its administration costs) on most species, and is under-recovering around $40 per m3 for High Country species* [104]

In their 2021 report, IPART's analysis of harvesting and haulage costs indicates that at times, the hardwood business is not recovering its harvesting and haulage costs. The 2021 report[105] indicates that over the 2016 to 2019 period, the harvesting and haulage costs exceeded revenue, with an average shortfall of $3.96 per green metric tonne.

IPART noted that FCNSW received revenue from two sources to cover its harvesting and haulage costs:

- delivery charges to customers
- industry adjustment grants from the NSW Government, which relate to forestry policy changes on the South Coast.

The two revenue sources were not sufficient to cover the harvesting and haulage costs over the 2016 to 2019 period. IPART report that FCNSW has since increased its delivery charges to achieve cost recovery in the future.

Historical periods of unprofitability

FCNSW had negative earnings before income tax for over 10 years prior to 2014-15.[106]

Employment in the FCNSW hardwood business

Employment across all divisions

In their Annual Report, FCNSW report total employment across the organisation and do not separately identify staff by division. In 2020-21, FCNSW employed 549 full-time equivalent (FTE) staff including:

- 317 office based staff: involved in management, administration and technical roles
- 232 field based staff: field contractor management, road construction and maintenance, tree planting and pruning, nursery work, forest conservation and fire protection.

In addition to the head office in Sydney, operations are managed from regional offices in Coffs Harbour, Wauchope, Bathurst, Dubbo, Batemans Bay, and Tumut.[107]

104 IPART 2017, *Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report*, December, p. 8-9, 49

105 IPART 2021, *Review of Forestry Corporation's native timber harvesting and haulage costs*, p. 23

106 GHD 2017, *Review of Coastal Hardwood Wood Supply Agreements, Final Report*, March, p.3

107 FCNSW, *Sustainability Report 2020-21*, p. 31.

Hardwood division employment

A General Manager is in charge of the Hardwood Forests Division, which has the following teams[108]:

- Hardwood marketing and timber sales
- Native forest stewardship and fire management
- Forest management planning
- Timber harvesting and roading operations
- Ecological surveys and monitoring
- Hardwood plantations.

The key positions that would be impacted by ceasing FCNSW's native forest logging are the positions that manage the timber sales and harvesting and haulage operations.

Information provided to 2015 NSW Budget Estimates hearings indicated that Forestry Corporation employed 220 people in its hardwood division, including both the hardwood native and plantation timber operations.[109]

Harvesting and haulage operations management

Indufor estimated[110] Forestry Corporation's administration cost based on staff costs associated with managing harvesting and haulage operations in the Northern and Southern regions. This includes 14 full time equivalent (FTE) staff dedicated to management, supervision and coordination of contractors and an additional 19 positions, whose roles are 50% attributed to managing harvesting and haulage operations .

108 FCNSW, *Annual Report 2020–21*, p. 23.

109 National Parks Association of NSW, 'Regional Forest Agreement have not worked economically or socially', viewed 25 April 2022, available at: https://npansw.org.au/wp-content/uploads/2016/10/npa_regional-forest-agreement-have-not-worked-economically-or-socially.pdf

110 IPART 2021, *Review of Forestry Corporation's native timber harvesting and haulage costs*, p.23 and further detail in Indufor 2021, *Native Forest Harvest and Haulage Review and Benchmarking, Final Report*, 1 February, p. 82.

B NSW native forest processing sector

This attachment provides information on the current size of the processing sector that uses FCNSW's supply of native forest logs and details on employment levels, location and economic contribution to NSW regional communities. We note that the size of the industry has been declining over time as the level of wood supply has fallen.

Wood supply from native forests has suffered another significant downward shock due to the 2019-20 bushfires which is currently further impacting the viability of the native forest processing sector.

In this report, we report on direct employment in the processing sector, which is defined to include harvest and haulage contractors and primary wood processors (e.g. sawmills, chipmills, and pole producers). We do not report on downstream sectors including truss and frame producers, furniture manufacturers or timber sales and distribution.

Key hardwood processing employment centres are around Eden, Narooma, Batemans Bay, Nowra, Tumbarumba, Grafton, Kyogle, Casino, Coffs Harbour, Kempsey, Wauchope, Taree and Bulahdelah.

Taking the most recent employment estimates from the NRC, direct employment in the native forest-related harvest and haulage and mills prior to the 2019-20 bushfires was in the order of 332 in the South Coast sub regions and 590 in the North Coast sub regions. The NRC has estimated that this could fall to around 155 and 500 direct jobs, respectively, if their recommendations are implemented.

The NRC defines the direct jobs as:[111]

> *jobs involved in the forestry supply chain from the point of forest management and harvest planning and operations, through to and including primary processing of the log products.*

111 NRC 2021, *Advice on Coastal IFOA operations post-2019-20 wildfires, Final Report*, June, p. 37.

Table 7: NRC direct employment estimates

Region	2019-20 (pre-fire)	After NRC recommendations
South Coast	67	13
Eden	250	130
Tumut	15	12
Total South Coast	**332**	**155**
North Coast	**590**	**500**
Total South and North Coast	**922**	**655**

Source: NRC 2021, Advice on Coastal IFOA operations post-2019-20 wildfires, Final Report, June

As well as the North and South Coast regions shown above, as shown in **Table 7**, FCNSW's hardwood business also supplies wood from its Western Region. The Western Region business supplies red gum and white cypress to processors.

Of the Western Region WSA holders (shown in **Table 10** below), there are two redgum sawmills and a white cypress processor with two mills (in Narrandera and Condobolin) and a number of red gum firewood suppliers.

Employment among these processors receiving red gum and white cypress native timber under WSAs with FCNSW is estimated to be in the order of 125 - 150 employees. This is based on reported information on employment levels at the mills and inferred levels of employment given the volume of wood supply.

Further detail on the harvest and haulage and processing sectors that is useful in estimating potential structural adjustment assistance is provided below.

Harvest and haulage

Contracting arrangements

Harvest and haulage contractors are retained by either by FCNSW or directly by the mills to harvest the wood and haul it to the milling facilities, depending on the nature of the log sales.

Harvesting operations involve tree felling, skidding the logs to roadside, log grading and roadside storage. Haulage operations involve loading logs onto trucks and transportation to mills.

Under the delivered price or a mill door sales arrangement, FCNSW arranges for harvesting and haulage to the sawmill and charges a bundled price that includes the harvesting and haulage and stumpage. According to IPART delivered price arrangement are largely used for low-quality and high quality sawlogs sales, accounting for around 62% of FCNSW's native timber production.

Under stumpage sales, the sawmill has a right to harvest timber from a specific forest. In this case, the sawmill only pays FCNSW a stumpage price. It contracts directly for harvesting and haulage services. According to IPART, stumpage is primarily used in the West Region and Eden Forest Management Areas.[112]

Harvesting and haulage contractors are small, privately owned businesses that may operate in more than one state.

FCNSW's harvesting and haulage contracts are generally up to 5 years in length, allowing contractors to finance equipment.

Number of native forestry related harvest and haulage contractors involved in mill door/delivered sales

IPART report that in 2019, there were 33 harvesting contractors and 10 haulage contractors serving FCNSW's delivered sales.[113](IPART, p.41)

The Benchmarking Report prepared for IPARTs consultant, Indufor, provides detailed information on harvest and haulage contractors. This indicates that:[114]

- Harvesters are geographically based. Over the period from 2017-19, FCNSW contracted with one large, 5 medium and 27 smaller harvesters. Eight of the businesses were vertically integrated harvest and haulage operators.
- FCNSW contracted with one large haulage consortium (North Haul) on the North Coast, 4 medium and 5 small haulage contractors.

The table below summarises the number of harvesting and haulage contractors.

Table 8: FCNSW delivered sales harvest and haulage contractors

	Upper North	Lower North / Central	South	South West
Harvest	13	12	8	3
Haulage	4	3	1	2
Vertically integrated	4 [1]	3 [1]	7	2

Source: Indufor 2021, Native Forest Harvest and Haulage Review and Benchmarking, Final Report, 1 February, p. 68. 1: Includes the 3 contractors that have formed the North Haul consortium).

Contractors servicing stumpage sales

As noted above, mills in the Western Region and Eden Forest Management Areas purchase hardwoods logs on a stumpage basis. Hence, these mills retain the harvesting and haulage

112 See IPART 2017, *Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report*, December and IPART 2021, *Review of Forestry Corporation's native timber harvesting and haulage costs*,

113 IPART 2021, *Review of Forestry Corporation's native timber harvesting and haulage costs*, p. 41.

114 Indufor 2021, *Native Forest Harvest and Haulage Review and Benchmarking, Final Report*, 1 February, p. 62-68.

contractors themselves. In some cases, there are also integrated haulage and processing businesses. For example, ARH Contracting which supplies red gum firewood.

Data on the number of harvest and haulage contractors supplying the Western and Eden regions has not been found. We note that the log volumes being harvested and hauled in the Western and Eden region are significantly lower than in the other native hardwood supply regions.

Capital requirements of harvesting and haulage

Indufor (p. 36) report that typical capital costs for a standard 3 machine harvesting crew are in the order of $1.2 million to $2 million. Financing costs are in the order of $0.6 million to 1 million per harvesting crew.

Wood processors

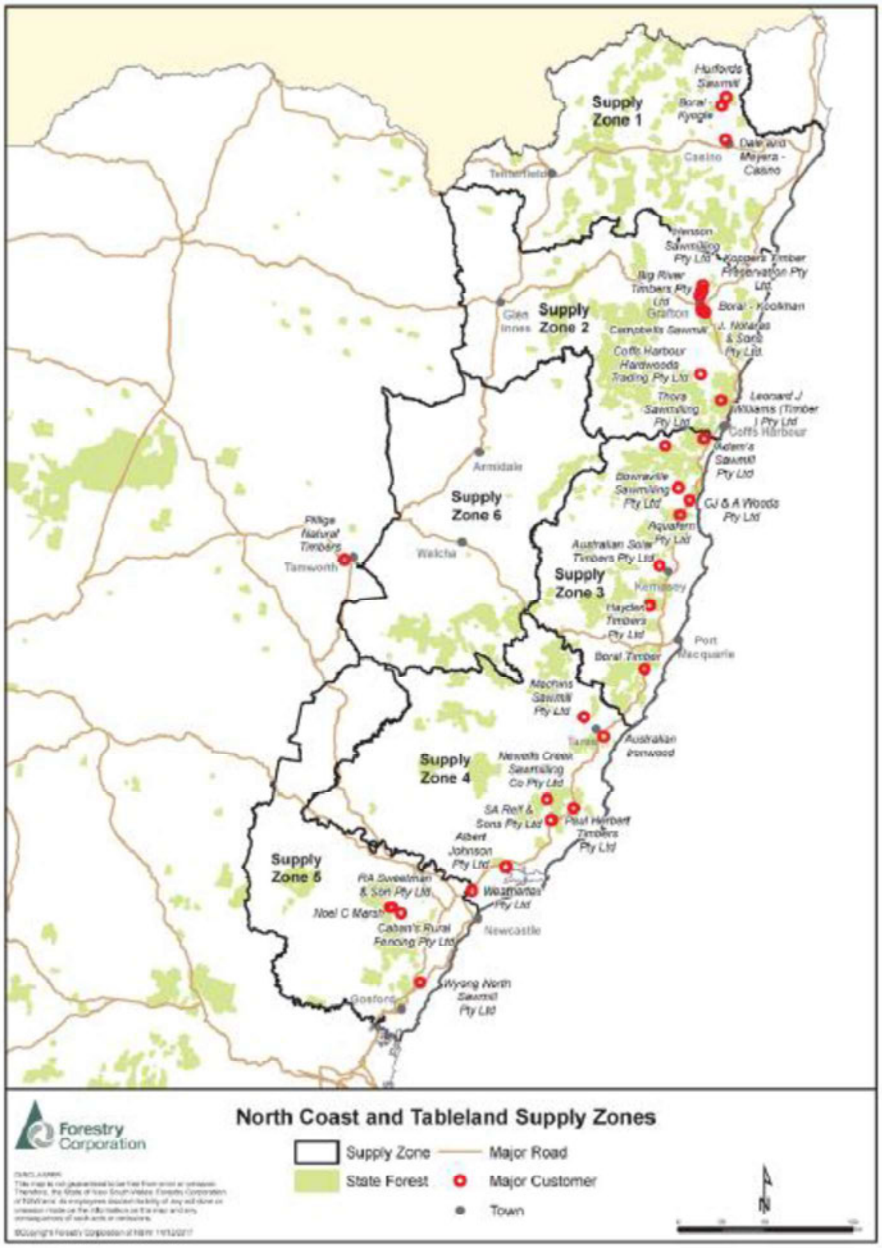
Over financial year 2017 to 2019, FCNSW sold native forest logs to: 130 mill door sales customers; 5 stumpage sales customers, 21 combined stumpage and delivered sales customers. [115] The location of the costal mills is shown in **Figure 12** and **Figure 13**.

[115] Indufor 2021, *Native Forest Harvest and Haulage Review and Benchmarking, Final Report*, 1 February, p. 14.

Figure 12: Location of hardwood sawmills

Source: GHD 2017, Report for NSW Department of Primary Industries – Review of Coastal hardwood Supply Agreements, p. 4.

Figure 13: FCNSW's native timber supply zones and major customers on the North Coast



Source: IPART 2017, Review of Forestry Corporation of NSW's native timber harvesting and haulage costs, Final Report, December, p. 23

Wood supply agreements

The largest processors have traditionally received their wood supply from FCNSW under long term (20 year) wood supply agreements. The majority of WSAs are due to expire in 2023. However, the Boral Wood Supply Agreement on the North Coast (which specifies quantities by species including Blackbutt and is a challenging contract for FCNSW to service) does not expire until 2028.

The coastal region WSAs are shown in **Table 9** and the Western region WSAs in **Table 10**.

Table 9: Wood supply agreements: Coastal

Company	Mill Locations	Product	Contract Term[1]	Sale Type	Allocation Total (m^3 or gmt per annum)
Allied Natural Wood Exports	Edrom	Pulplog	2018 - 2033	Stumpage	290 000
Allied Natural Wood Exports	Edrom	Sawlog	2020 - 2029	Stumpage	25 000
Boral Timber	Koolkhan Herons Ck, Kyogle	High Quality Sawlogs	2004 - 2028	Mill door	163 000
	Narooma, Nowra	High Quality Sawlogs	2001 - 2020		
Thora Sawmilling Pty Limited	Thora	High Quality Sawlogs, Low Quality Sawlogs	2004 - 2023	Mill door	42 627
Hurfords Hardwood Kempsey Pty Ltd	West Kempsey	High Quality Sawlogs, Low Quality Sawlogs	2004 - 2023	Mill door	8 123
Newells Creek Sawmilling Co. Pty Ltd SA Relf & Sons Pty Ltd	Bulahdelah	High Quality Sawlogs, Low Quality Sawlogs	2004 - 2023	Mill door	19 807
Adams Sawmills Pty Ltd	Bonville	Low Quality Sawlogs	2004 – 2021	Mill door	21 863
Hurford's Building Supplies Ltd	Kyogle, Casino, Karuah, Tuncester	High Quality Sawlogs, Low Quality Sawlogs	2004 - 2023	Mill door	21 753
Koppers Wood Products Pty Ltd	Junction Hill	Poles and Piles	2004 - 2023	Mill door	20 260
Aquafern Pty Limited	Warrell Creek	Low Quality Sawlogs	2005 - 2023	Mill door	18 000
Hayden Timbers Pty Ltd	Telegraph Point	Low Quality Sawlogs	2006 - 2023	Mill door	17 925
CJ & A Woods Pty Limited	Nambucca	High Quality Sawlogs, Low Quality Sawlogs	2007 - 2023	Mill door	7 182
J Notaras & Sons	Grafton	High Quality Sawlogs, Low Quality Sawlogs	2004 - 2023	Mill door	16 579
Big Rivers Timbers	Junction Hill	Veneer Logs	2004 - 2023	Mill door	16 502
Weathertex Pty Ltd	Heatherbrae	Pulplog	2023	Mill door	21 000
Ryan & McNulty Pty Ltd	Benalla	High Quality Sawlogs	2004 - 2030	Mill door	18 500
Braidwood Sawmill	Braidwood	High Quality Sawlogs, Low Quality Sawlogs	2020	Mill door	5 886
Williams Timber Pty Ltd	Bucca	Poles, Piles, Girders, High Quality Sawlogs, Low Quality Sawlogs	2023	Mill door	4 550
Other (63 entities)	Various	Various	Various		>1000

Source: Indufor 2021, Native Forest Harvest and Haulage Review and Benchmarking, Final Report, 1 February, p. 12-13.

FCNSW reports that in 2019 it supplied native timber to more than 16 customers, with the volume of supply varying between less than 1,000 m3 to over 20,000 m3 per annum. [116] As shown in **Table 10**, FCNSW has had WSAs with 11 processors in the Western Region. Only two of these agreements appear to extend beyond mid-2022 (for a redgum mill in Victoria and white cypress mills in NSW).

116 FCNSW Hardwood Forests Division 2019, Forest Management Plan for the Western Forests of NSW, p. 42.

Table 10: Wood supply agreements: Western region

WSA holder	Business and location	WSA term	WSA annual volume	Employees
Arbuthnot Sawmills (Logs)	Redgum timber milling, furniture, firewood Koondrook Victoria	To 30 June 2030	4,613 m3	15 FTEs Use 6 logging contractors in NSW and VIC [1]
ARH Contracting (Residue)	Red gum firewood Balranald NSW	To 30 June 2022	11,000 tonnes	n.a
Campi Bulk Haulage (Residue)	Red gum firewood Barham, NSW	To 31 December 2020	1,748 tonnes	n.a
Forest Logging Contracting (Residue)	Red gum firewood Balranald NSW	To 30 June 2022	11,000 tonnes	n.a
Gelletly (Residue)	Red gum firewood Barham, NSW	To 30 June 2019	20,000 tonnes	n.a
Grants Baradine Sawmill [2]	White cypress mills Narrandera and Condobolin, NSW	Unclear – at least to 30 June 2026	14,390 m3	n.a.
Mathoura (Red Gum)	Redgum timber milling Mathoura, NSW	To 31 December 2020	4,178 m3	n.a

WSA holder	Business and location	WSA term	WSA annual volume	Employees
O'Briens Sawmills (Red Gum Thinnings)	Red gum firewood Barham, NSW	To 30 June 2019 (maximum term)	22,250 tonnes	n.a
Peter Strange (Red Gum)	Redgum residue	To 31 December 2020	2,356 tonnes	n.a
Rameus September Nominees (Gelletly)	Redgum Horfield, Victoria	To 30 June 2019	17,500 tonnes	n.a
TRT Pastoral (Red Gum)	Juanbung Mill (firewood) Near Balranald, NSW	To 30 June 2022	11,000 tonnes	n.a

Notes:
1 https://www.arbuthnotsawmills.com.au/about-us/ accessed 20 May 2022.
2 Grants Holdings Co Pty Ltd was given a $1 million grant by the NSW Government in 2021 to recommission Baradine Sawmill and install new machinery and upgraded equipment. It was reported that this would support the creation of 50 full-time jobs. https://www.nswnationals.org.au/nats-in-government-back-warrumbungle-sawmill/ accessed 19 May 2022.
Source: Frontier Economics and Forestry Corporation NSW https://www.forestrycorporation.com.au/about/sales-and-supply accessed 19 May 2022

Capacity of the hardwood mills

Hardwood sawmills tend to be much smaller than softwood mills, given the nature of the native resource and need to be located relatively close to the forest resource. ABARES data shows that the average capacity of the NSW hardwood mills was 3,785 m3 per mill in 2016-17.

Table 11: NSW hardwood mill characteristics 2016-17

	No of mills	Total input ('000 m3)	Average input (m3/mill)	Recovery rate (%)	Average output (m3/mill)	Total output ('000 m3)
NSW hardwood sawmill	68	620	9,121	41.5	3,785	257

Source: Downham, R, Gavran, M & Frakes, I 2019, ABARES National Wood Processing Survey: 2016–17, ABARES technical report 19.3, Canberra, June, p. 6

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Natural Resources Commission

NSW Forest Monitoring and Improvement Program

Insights for NSW forest outcomes and management

November 2022

Enquiries

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Acknowledgement of Country

The Natural Resources Commission acknowledges and pays respect to traditional owners and Aboriginal peoples. The Commission recognises and acknowledges that traditional owners have a deep cultural, social, environmental, spiritual and economic connection to their lands and waters. We value and respect their knowledge in natural resource management and the contributions of many generations, including Elders, to this understanding and connection.

List of acronyms

CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPE	Department of Planning and Environment
DPI	Department of Primary Industries
EES	Energy, Environment and Science
FFDI	Forest Fire Danger Index
FMIP	Forest Monitoring and Improvement Program
IFOA	Integrated Forestry Operations Approval
NSW	New South Wales
RFA	Regional Forest Agreement
SOC	Soil organic carbon

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Table of contents

Executive summary

NSW forests whether they be national parks, state forests, Aboriginal land, private land or Crown land are under sustained threats, putting at risk many of the services and values they provide. These findings are the consensus of independent scientific advisors, senior forest managers and research commissioned by the Natural Resources Commission (the Commission) over the three years of the Forest Monitoring and Improvement Program (FMIP).

The FMIP has reviewed existing data and commissioned new monitoring and research to substantially advance our understanding of the status of NSW forests, how they have changed over the last 30 years, and their outlook. Learning from the past 30 years and looking forward to 2050, now is the time for the NSW Government to proactively and holistically set the future directions for NSW forests in collaboration with communities, industry and First Nations people.

NSW forests are dynamic systems that provide essential environmental, social, economic and cultural services for the people of NSW across a range of tenures. These services are degrading, and without major intervention they will continue to degrade. The unprecedented bushfires of 2019-2020 will not remain an outlier. The research community had predicted the likelihood of such an event and the scientific consensus is that similar scale events will become increasingly frequent in the future.

Other drivers such as invasive species, population growth, economic growth and intensification of urban and agricultural land uses will continue to place increasing demands and pressure on NSW forests. Business-as-usual management approaches and reactive policy decision making will lead to sub-optimal outcomes at best, or ecosystem and industry collapse under worst case scenarios.

Forest use and management is a highly contested space. For example, the native forestry sector is subject to significant community scrutiny and policy shifts. Other jurisdictions are experiencing major policy shocks as decisions have been made on the future of native timber harvesting – for example, ceasing future harvesting in Western Australia and Victoria - with some stakeholders questioning the strength of the evidence base for those decisions. All sectors that rely on NSW forests – for example, nature-based tourism, apiary, water supply utilities - are now subject to the additional stress of a shifting climate in which droughts, floods and fires are likely to occur more frequently and intensely.

In NSW, the Regional Forest Agreements (RFAs) were renewed in 2018 on the premise that the RFAs would continue to be implemented through the NSW Forest Management Framework, which included a commitment to enhanced monitoring and research. The FMIP was the NSW Government's response to address knowledge gaps and deliver an improved evidence base to inform NSW forest management. At the same time, there have been a series of inquiries into bushfires, koalas and most recently, the forestry industry.

While these inquiries have recommended opportunities to improve forest outcomes, there is a risk that decision making and investment in response to these inquiries is occurring in isolation of each other and a wider international context – for example - increasing demand for sustainable forest products and new market initiatives for natural capital.

Recent NSW and Australian State of the Environment reports identify the same repeated issues of species decline, increasing risks and inadequate management responses. A more strategic focus on NSW forests across all tenures, drawing on the extensive evidence base collected through the FMIP, is essential to ensure they are more resilient and continue to provide their diverse services for future generations.

NSW forests are exhibiting many indicators of stress and degradation

Findings emerging from the FMIP indicate that NSW forests are under significant pressure from increasing shocks such as extended periods of drought and increasing fire frequency and severity coupled with ongoing threats such as pests and weeds.

Findings for key themes include:

- **forest canopy cover extent –**relatively stable on public land between 1995-2019, with increases of up to 12 percent on private land, followed by a steep decline due to the 2019-20 wildfires, particularly affecting state forests and national parks and subsequently followed by recovering canopy cover after significant rain events post-fires.
- **forest carbon** – the forests of NSW contain a large store of carbon (total forest carbon stock estimates between 1990-2019 were consistently over 2,250 million tonnes), with significant carbon emissions from NSW coastal forests due to fire – the 2019-20 wildfires alone released around 90 million tonnes of forest biomass carbon. A detailed account of carbon stored in all NSW forests 1990 to the end of 2020 found a net loss of carbon primarily due to the 2019-20 wildfires. The frequency and severity of future bushfires will likely determine the scale of future net carbon losses.
- **biodiversity** –
  - fauna occupancy trends could only be assessed for 28 of 520 fauna species; of those assessed, some such as the Powerful Owl and Sooty Owl show signs of recovery from a near zero base between 1998 and 2011, while the Greater Glider declined in the same period and koalas were stable in north-east hinterland forests since regular monitoring started in 2015.
  - introduced species, particularly feral cats and foxes, were widespread across both northern and southern coastal forests and pose a significant threat to biodiversity.
  - only 10 percent of forested vegetation in the NSW Regional Forest Agreement areas are currently within their recommended fire frequency thresholds, with large areas at risk of a decline in plant biodiversity due to increased fire frequency. As noted above, the scientific consensus is that fire frequency and intensity will increase across NSW.
- **forest water catchments** – catchment water flows have been declining in forested areas over the last 30 years, especially on the south coast of NSW. Almost half of the 90 catchments analysed showed statistically significant decreases in stream flows in this period, presenting a major challenge to water security for all water users during droughts.
- **soil health and stability** – soil organic carbon has fluctuated, with minor declines 2010 to 2019 driven largely by climate and wildfires, and significant declines expected following the 2019-20 wildfires; in general, more heavily disturbed private forests were found to have less soil organic carbon, particularly grazed forests.
- **Aboriginal cultural values** – large knowledge gaps remain around Aboriginal cultural values in NSW forests across public and private tenures, with Aboriginal people not adequately involved in land management and decision making.
- **productive capacity and sustainability** – total hardwood supply in the Coastal IFOA region declined between 2003-19 for both high and low quality logs, with additional significant short-term reductions in hardwood supply and projected sustainable timber yields following the 2019-20 wildfires, particularly on the south coast.

In the past decade the most significant driver of observed change was the 2019-20 wildfires. Initial FMIP baselines and trends studies were extended to assess the impacts of these fires, with analysis showing sharp declines in indicators such as forest canopy cover extent and forest carbon stocks across both state forests and national parks. Hot, dry climatic conditions were a key factor exacerbating the severity, extent and impacts. These fires were more intense in southern coastal NSW than in northern coastal NSW.

Forest canopy recovery is already underway following the 2019-20 wildfires, particularly on the NSW north coast. However, affected areas are considered particularly vulnerable in the next 5 to 10 years, with a risk that subsequent disturbances or threats could undermine forest recovery and carbon capture in these areas. In addition to threats from fire and drought, other factors such as loss and degradation of habitats and invasive species also continue to have a negative impact on biodiversity and forest values and may affect post-fire forest recovery. It is uncertain what the cumulative impacts maybe from the shock of the fires, followed by extensive flooding and the future resumption of intensive harvesting.

Forests face a challenging future under climate change

The climate across NSW is predicted to become more variable in the future, with increasing periods of both drought and intense rainfall, bringing heightened fire and flood risks. Under various climate scenarios, maximum temperatures are expected to rise between 0.4-1°C now and into the near future (2020-2039) and 1.8-2.6°C in the far future (2060-2079). The consensus of the scientific community is that the predicted swings between drought and floods are just as significant as the overall heating of the climate.

FMIP research indicates future climate and disturbance regime scenarios will have adverse impacts on NSW forests, affecting forest carbon, soil organic carbon, soil alkalinity, streamflow quantity, surface water quality and forest productivity. Many forest dependent flora and fauna species are predicted to lose significant proportions of their habitat. As a result, one FMIP study found the potential occupancy of 70 percent of assessed fauna species will decline by 2070 under future climate change predictions.

Critically, there is a risk that higher frequency and intensity of disturbances will trigger ongoing cycles of decline in key areas such as forest regeneration and soil organic carbon by reducing the capacity for, or likelihood of, full recovery after each event. In this case, forests will become a net carbon emitter in the coming decades, undermining key Government commitments to achieve net zero carbon emissions by 2050. Other Government commitments for biodiversity and sustainable production outcomes will also be under pressure.

NSW regions like the Australian Alps and South Coast, that have significant areas dedicated to the reserve system, are anticipated to be at highest risk from projected changes in climate and fire regimes. Other forest ecosystems such as temperate and sub-tropical rainforests are also under increasing risk.

Strategic action is needed to prevent loss of future forest values and services

In the absence of a strategic approach, existing stressors will combine with increased threats from climate change and repeated shocks from natural disturbances like droughts, fires and floods and lead to ongoing declines in the resilience, health and productivity of NSW forests. These threats do not recognise tenure boundaries, nor likely to be mitigated by piecemeal solutions which may result in only incremental outcomes.

In this context, it is likely that the many values and services provided and supported by NSW forests – including their role in carbon capture and storage and water security - may change in the future, particularly in high-risk regions.

More positive futures are possible with increased recognition of – and investment in – the social, cultural and economic values of forests, and by actively addressing emerging risks from climate change. This is recognised in the *NSW Climate Change Adaption Strategy* that outlines priorities and actions for NSW to adapt to climate change. To support this, a targeted strategy for NSW forests outlining the best course of action needs to be carefully assessed and debated based on the best science and dialogue with the community and industry.

Success will rely on mutual understanding and bipartisan support for proposed actions to improve future outcomes for NSW forests. The FMIP has delivered the foundations for this work including scenario analysis, modelling and projections based on historical datasets, research and expert advice.

This report identifies key opportunities to maintain and improve forest values, improve forest resilience and reduce risk exposure over the long-term.

The **Commission recommends** the NSW Government:

1 Prepare an overarching cross-tenure strategy for *NSW forests towards 2050* to systematically address the threats of climate change and other stressors. In developing this strategy, Government should:
   - 1.1 assess the full range of environmental, social, economic and cultural values and uses of forests across tenures supported by the future forest scenarios developed under FMIP
   - 1.2 identify and assess:
     - i. most at-risk forest-dependent ecosystems, threatened species and forest-dependent communities and industries under climate change
     - ii. areas demonstrating strongest trajectories of recovery post 2019-20 wildfires
     - iii. potential options and trade-offs between management response and outcomes.
   - 1.3 identify strategic investments and actions to pro-actively protect assets, reduce risks and accelerate outcomes
   - 1.4 ensure it provides for increased Aboriginal involvement in decision making and forest management
   - 1.5 in preparing the strategy:
     - i. consult meaningfully with community, Aboriginal peoples, industry and scientific experts, including preparing regionally targeted future forests scenarios as a means of engagement
     - ii. consider the rights and interests of respective land-owners
     - iii. draw on the latest science and data, including baselines developed under the FMIP.

2 Establish a dedicated fund to:
   - i. Support implementation of the *NSW forests towards 2050 strategy*
   - ii. Support rapid response to protect forest assets and address risks during or after significant climate events
   - iii. Trial large scale research-based interventions across tenures to reduce vulnerability to wildfires, including use of Indigenous burning practices.

3 Accelerate Aboriginal self-determination and co-management of NSW forests through a variety of mechanisms, including whole of Country planning, joint management, and Indigenous Land Use Agreements.

4 Incorporate latest climate science and forest data into upcoming review of the Coastal Integrated Forestry Operations Approval and other existing regulatory mechanisms across tenures.

5 Review and update the *NSW Forestry Industry Roadmap* in collaboration with industry incorporating the latest climate science, economic data and industry outlooks.

6 Continue long-term independent research and monitoring to improve evidence base for adaptive decision making, namely:
   - i. improving tracking forest carbon balances for national and state carbon accounting to support NSW Government’s commitments to achieving net zero carbon emissions by 2050

ii. extending existing monitoring programs for public and private production forests to document how these forests are changing, the effectiveness of management and support periodic regulatory reviews and bilateral NSW and Australian Government commitments to ecological sustainable forest management

iii. ensuring consistent methods and datasets are applied across tenure to provide reliable performance information on management and outcomes.

1 Forest monitoring and research insights

Forests deliver a wide range of ecological, social, cultural and economic benefits for the people of NSW. Forest management seeks to maintain these benefits into the future, including through active interventions to address key threats or emerging risks such as a changing climate or intensification of land use. Forest management is undertaken across a range of tenures, including state forests, national parks, private native forests, Aboriginal land and Crown forested land. Decisions we make now about how our forests are managed will determine the extent to which these benefits can be delivered in the future. As such, it is critical that these decisions are evidenced-based and forward-looking.

Over the last four years, the NSW Forest Monitoring and Improvement Program (FMIP, see **Attachment A**) has commissioned a series of monitoring and research projects to determine the status of NSW forests, understand how they have been changing over the last 30 years and what their future outlook may be. These projects have generated baseline, driver and trend evidence across themes such as forest ecosystem health, biological diversity, soil and water resources, productive capacity and sustainability, and forest carbon, as well as insights into Aboriginal cultural values.

These projects have been instrumental in providing an empirical foundation for informed decision-making regarding forest management supported by ongoing monitoring and evaluation. This report brings together the findings from the FMIP – along with relevant findings from other related programs such as the Coastal Integrated Forestry Operations Approval (IFOA) monitoring program – to identify overarching lessons for forest management in NSW into the future. Findings for each FMIP theme are summarised in further detail in **Attachment A**, **Table B**.

1.1 Variable trends in forest indicators between 1995-2019

Prior to 2019, trends in forest indicators assessed under the FMIP varied, with examples of increasing, stable, fluctuating or declining trends to be found across the various FMIP themes.

Forest canopy cover extent showed a gradually increasing trend across NSW since 1995. By 2018, forest canopy cover extent in the Regional Forest Agreement regions[1] had increased by around 5 percent compared with 1995 figures (from 8.6 million hectares to 9.1 million hectares – an increase of around 518,580 hectares – see **Figure 1**).[2]

Most increases were on private land, where forest canopy cover increased by around 12 percent or 441,480 hectares. This is attributed to a thickening of cover in private tenures adjacent to public forest estates, or preservation of existing cover that is regenerating and thickening over time.[3] Forest canopy cover extent on national parks and state forests during this time remained largely stable.

Forest carbon was also largely stable across NSW during this period (**Figure 2**), with some regional variation driven by natural disturbances (fire, drought, natural regeneration) and anthropogenic activities (land clearing, reforestation, prescribed fire and timber harvesting).[4]

1 Regional Forest Agreements cover the Eden, North East and Southern regions of NSW. Forestry activities in these regions are regulated by the Coastal IFOA. Refer to **Section 3**, **Figure** for a map of these areas.

2 Natural Resources Commission - NSW Government (2022): NSW Forest Monitoring and Improvement Program RFA Historic Forest Cover Extent - 1995 to 2019. Version 1.0. Terrestrial Ecosystem Research Network. (Dataset). https://doi.org/10.25901/sayz-pb50

3 FMIP Project FE1: Baselines, drivers and trends for forest extent, condition and health – reporting by Spatial Vision to Natural Resources Commission (2021)

4 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

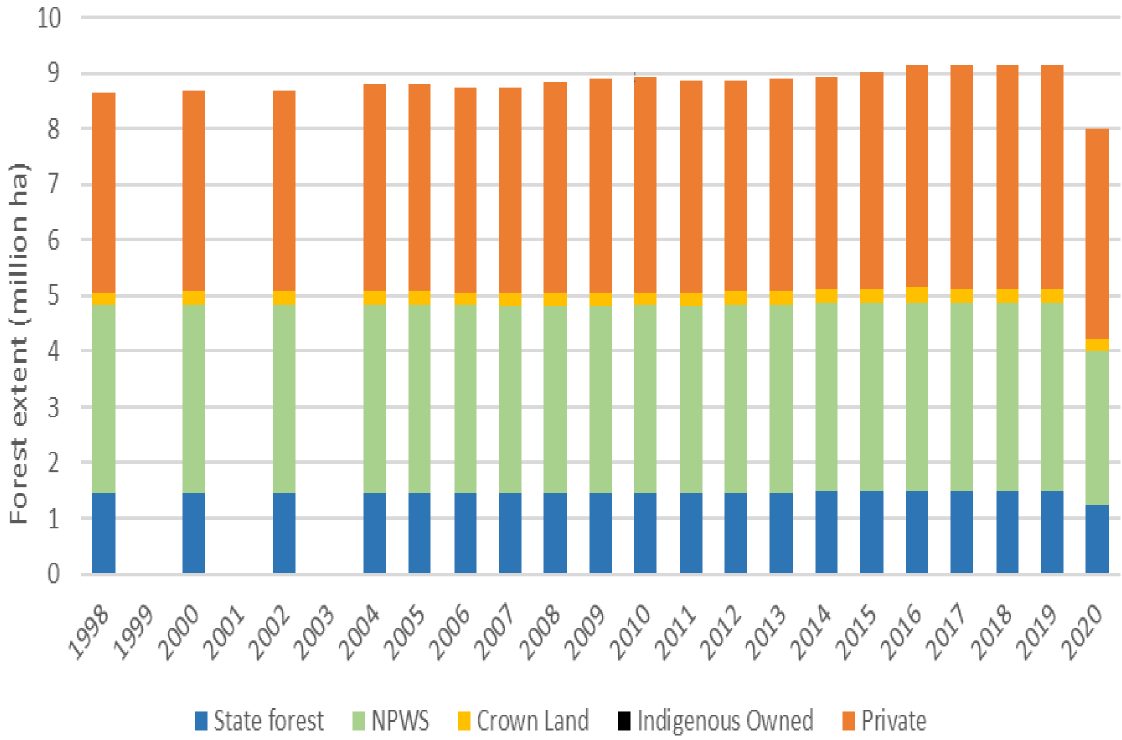

Figure 1: Change in forest canopy cover extent by tenure in the Regional Forest Agreement area (1998-2020)[5]

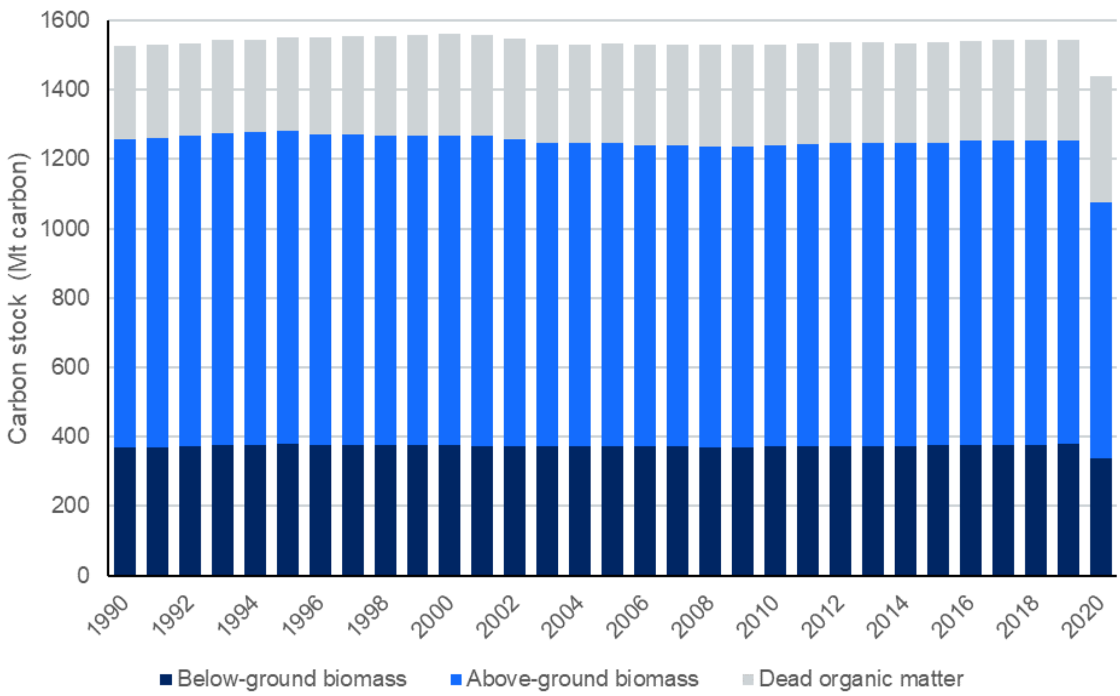

Figure 2: Total forest carbon for forests in the Regional Forest Agreement area (1990-2020)[6]

5 Spatial Vision (2022). *Forest Monitoring – Extent, Condition and Health – Overview Report*, unpublished report to the Natural Resources Commission

6 *Ibid.*

In contrast, FMIP studies indicated that soil organic carbon declined slightly over the last three decades, with significant fluctuations during this period attributed to climatic conditions such as temperature and rainfall.[7]

The quantity of streamflow has also been declining in forest catchments over the last 30 years, especially on the south coast of NSW (**Figure 3**).[8] This decline has been attributed largely to climatic variables such as rainfall, along with drought-related groundwater depletion and regeneration of vegetation following drought, fire or harvesting. Forested catchments supply water for a wide range of uses in NSW, so an ongoing, long-term reduction in streamflows from forested catchments has major implications for future water security in NSW.

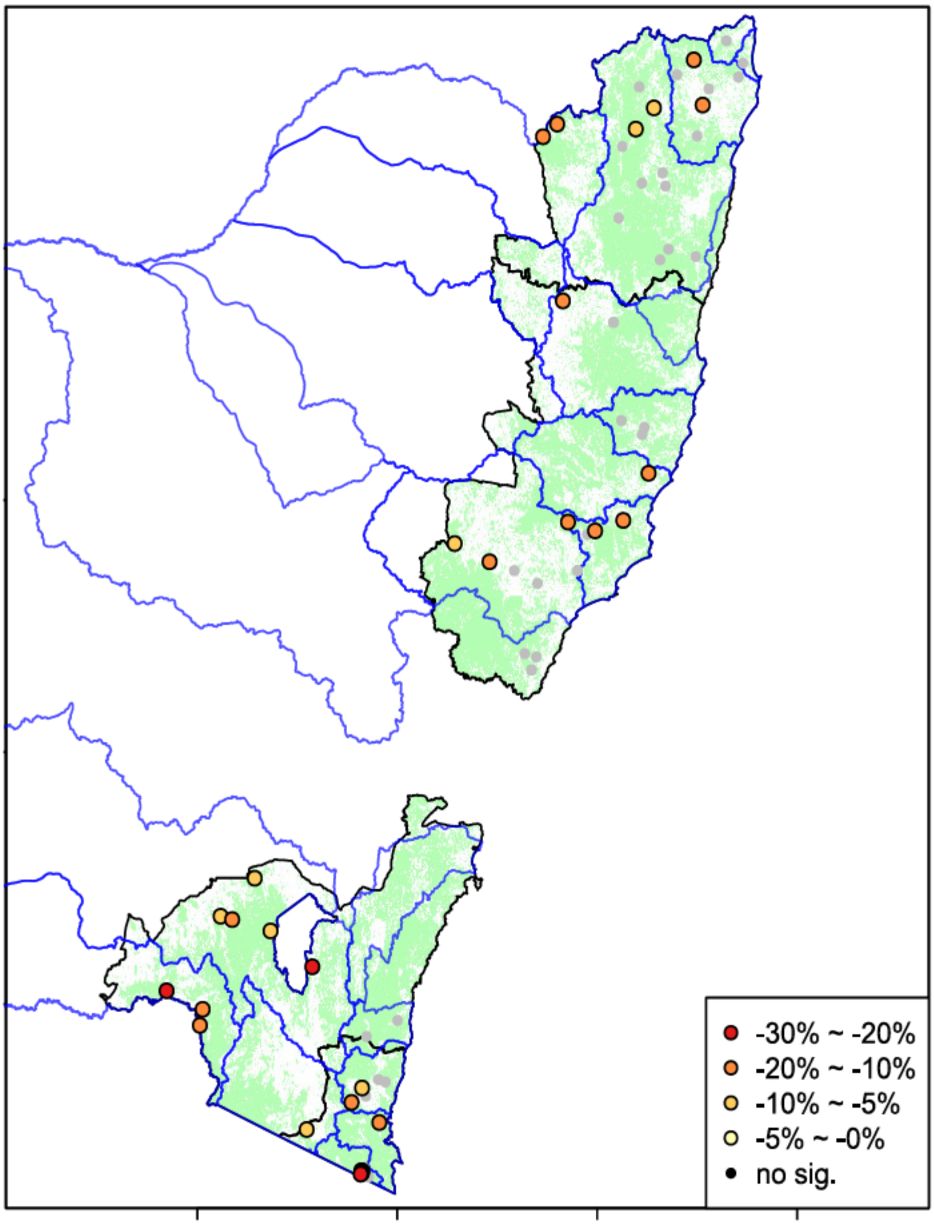

Figure 3: Magnitude of long-term trends in mean annual flow (percentage per decade)[9]

7 Moyce, MC; Gray, JM; Wilson, BR; Jenkins, BR; Young, MA; Ugbaje, SU; Bishop, TFA; Yang, X; Henderson, LE; Milford, HB; Tulau, MJ (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry & Environment and University of Sydney.

8 Guo, D., Hou, X., Saft, M., Webb, J.A., Western, A.W. (2010) *Report for NRC Forest Baseline & Trend Indicators - Project 3 Task 2 - Long-term trends of Water Quality and Quantity in NSW RFA forests*. University of Melbourne.

9 *Ibid.*

There were two major droughts during the assessment period, the Millennium drought from 1997 to 2009 (with an extremely dry period in 2002-03), and the 2017-19 drought.[10] Notably, the periods of drought and extreme dry conditions align with the recent fire history of Coastal NSW (**Figure 4**), with major fire events in both 2002-03 and 2019-20 following dry periods.

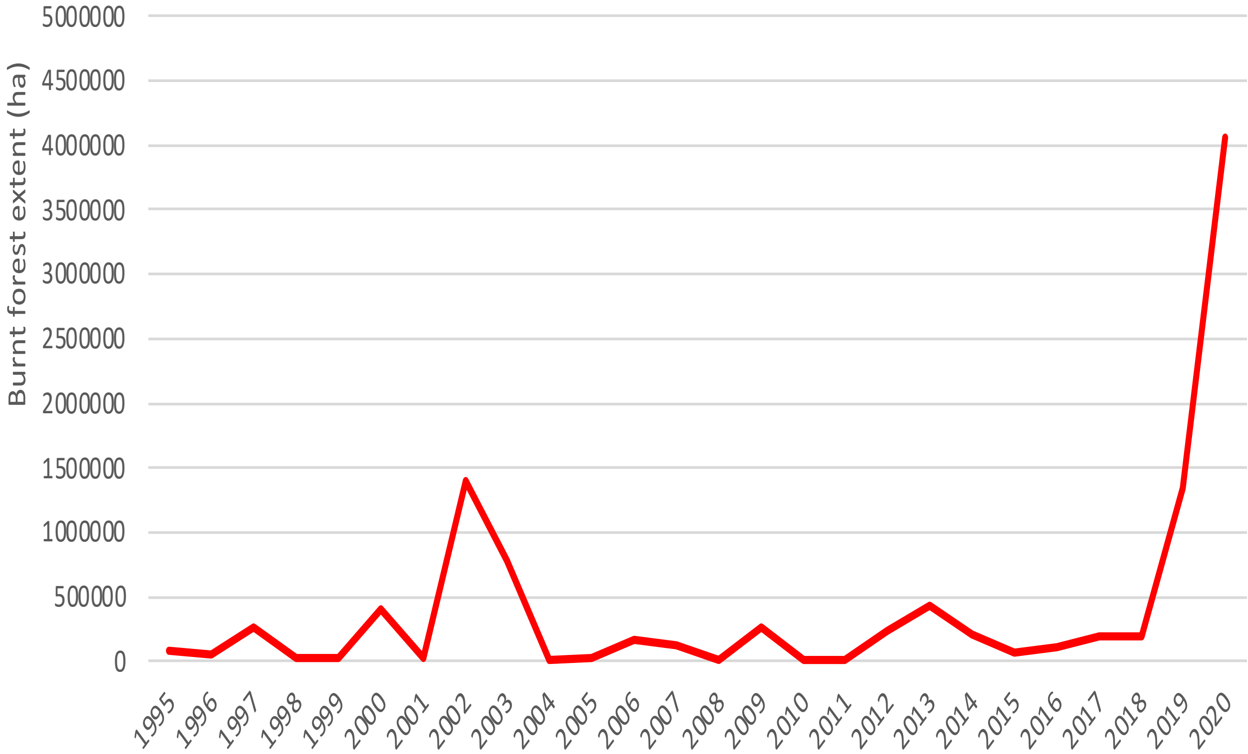

Figure 4: Fire history (burnt forest extent, hectares) for coastal NSW 1995-2020[11]

Total hardwood supply from public native forests and hardwood plantations in the Coastal IFOA region was observed to have declined in the period between 2003 and 2019 driven by resource availability, markets and supply chains (**Figure 5**). Hardwood pulplogs and low quality logs showed the largest decrease (around 40 percent by volume), while high quality hardwood sawlog supply decreased by around 15 percent. Overall hardwood supply and high-quality log supply were aligned to wood supply agreement allocations. On the North Coast IFOA sub-region, high and low quality hardwood supply declined by around 20 percent, while on the South Coast and Eden IFOA sub-regions high quality levels were maintained but there were significant declines for other hardwood products. All hardwood product volumes in the Tumut subregion varied considerably.

10 Bureau of Meteorology (2022). Previous Droughts, Commonwealth of Australia
11 Rural Fire Service composite wildfire layer, from 1995 to 2020

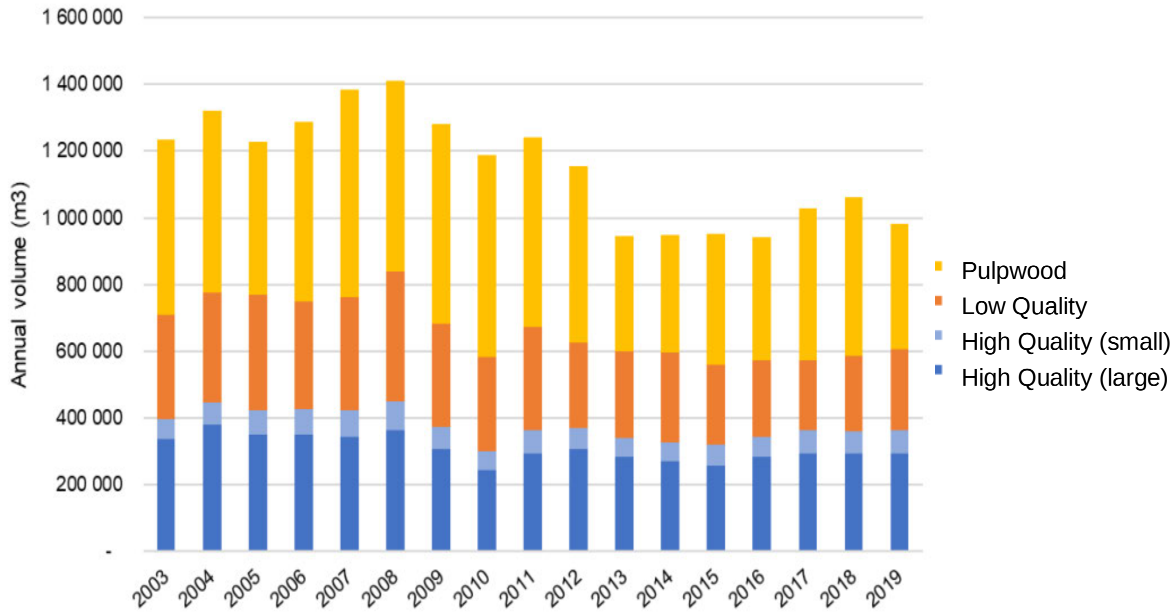

Figure 5: Hardwood supply from native forests and hardwood plantations in the Coastal IFOA region by type[12]

1.2 Significant declines in forest values due to wildfires

By far the largest change in forest indicators during the last 25 years occurred as a direct result of the 2019-20 wildfires. The data and analysis undertaken by the FMIP in establishing long-term baselines and trends for forest indicators allowed for rapid insights to be generated as to the scale of the impacts from this major fire event.

The 2019-20 fires were unprecedented in their extent (**Figure 6**) and severity (**Figure 7**), resulting in the largest total area burnt in a single recorded fire season in eastern Australia.[13] The 2019-20 event affected more than twice as much forested area compared with the 2002-03 fire event (**Figure 4**). Around 60 percent of forested areas across national parks and state forests were burnt in 2019-20.

12 Indufor (2022). *Coastal Integrated Forestry Operations Approval Monitoring Program - Monitoring wood supply baseline and trends.* Report prepared for the NSW Forest Monitoring and Improvement Program, Natural Resources Commission, Sydney N.S.W.

13 Bureau of Meteorology (2020) *Annual Climate Summary for New South Wales – 2019*, Bureau of Meteorology, Commonwealth of Australia, Canberra, ACT

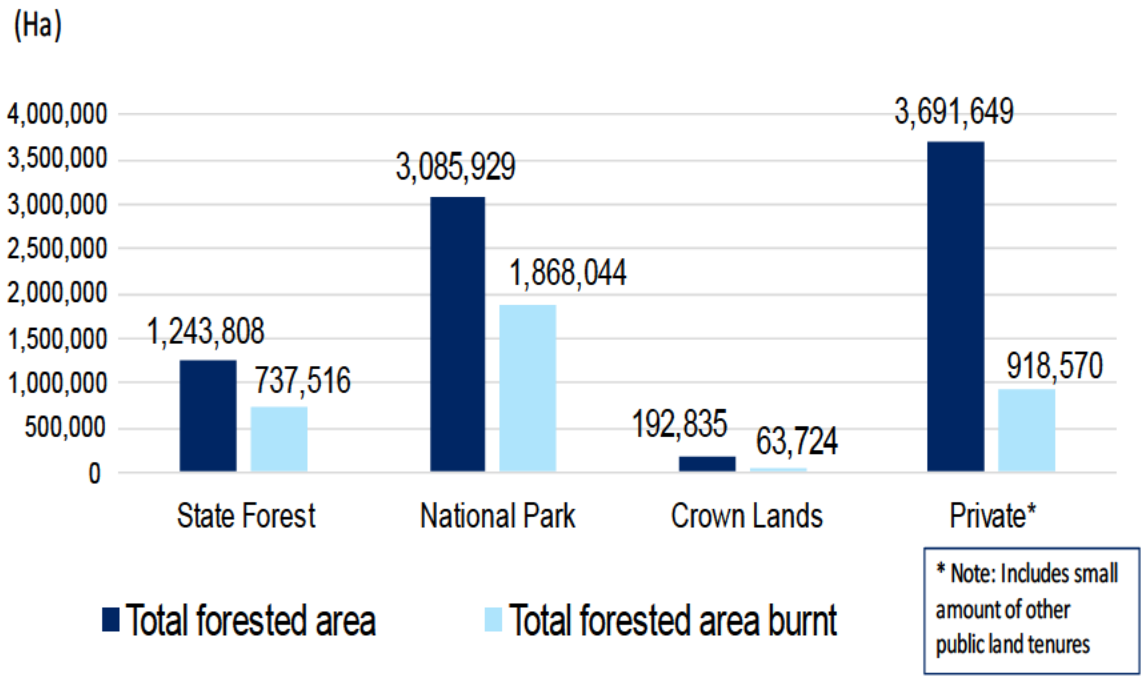

Figure 6: Fire extent for the 2019-20 fire season[14]

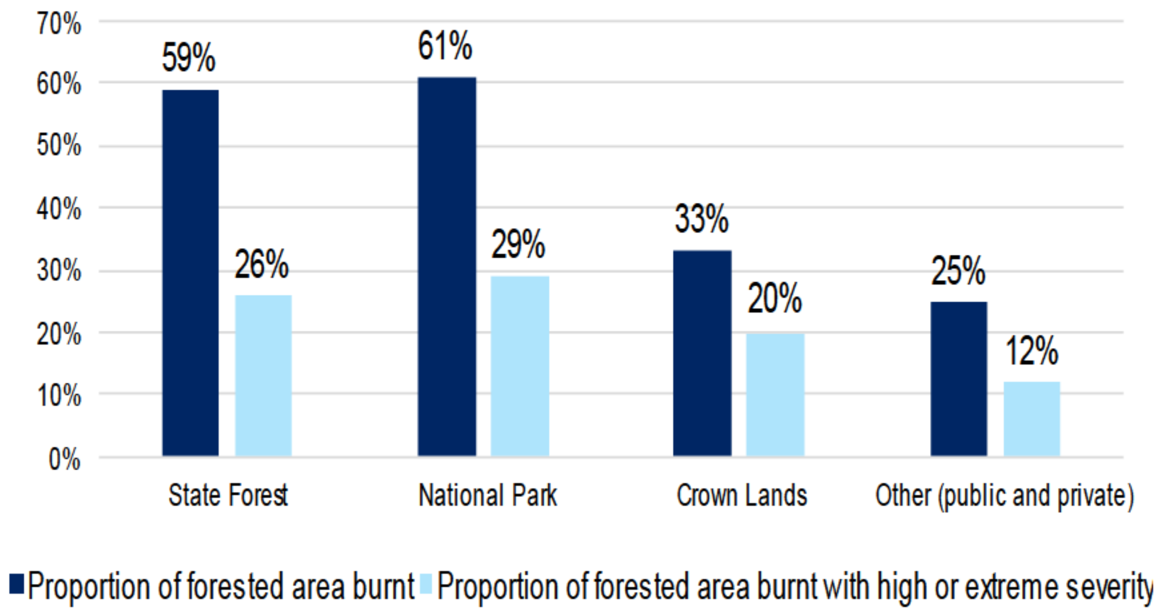

Figure 7: Fire severity for the 2019-20 fire season[15]

14 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

15 *Ibid.*

Hot, dry climatic conditions prior to the 2019-20 fire season exacerbated the severity, extent and impacts of the fires.[16] The final report of the NSW Bushfire Inquiry identified a range of causes and contributing factors, including extremely dry fuel on the ground due to prolonged and widespread drought, as well as repeated, extremely bad fire weather days combined with hot, low humidity nights.[17]

Regarding the impact of past forest management and timber harvesting, there is significant debate around the extent to which disturbance history influenced the 2019-20 wildfires. The 2019-20 wildfires burnt an extensive area, of which more than 90 percent had either never been harvested or had not been harvested within the last 20 years.[18] One study reported that past forest management, including previous timber harvesting, was not found to have increased the fire extent or severity of the 2019-20 wildfires.[19] Analysis across State Forests in the Coastal IFOA area also showed that patterns of burning and fire severity during the 2019-20 wildfires were unrelated to harvesting activities that had occurred within the previous 20 years (between 2000-2019).[20] However, another recent study suggests that timber harvesting increased the probability of high-severity fire in 2019-20.[21] Recent research in forests on the NSW south coast also shows a link between timber harvesting and increased risk of wildfire in fire-prone forests.[22]

Forest canopy cover extent

The 2019-20 fires led to significant impacts across coastal NSW and disproportionately affected public land tenures such as state forests and national parks. In the Regional Forest Agreement regions there were declines in forest canopy cover extent across public and private tenures between 2018 and 2020 as a result of the fires. On state forests and national parks, the fires reduced the forest canopy cover extent to levels significantly lower than the 1995 figures for these tenures (**Figure 8**). In contrast, the magnitude of previous gains in forest canopy cover on private land, combined with proportionally lower fire extent and severity, meant that there remained a net increase in forest canopy cover extent on private land post-fire.

16 Bowman, D.M.J.S., Williamson, G.J., Gibson, R.K. et al. (2021) The severity and extent of the Australia 2019–20 Eucalyptus forest fires are not the legacy of forest management. *Nat Ecol Evol* 5, 1003–1010.

17 NSW Department of Premier and Cabinet (2020), *Final Report of the NSW Bushfire Inquiry*, Sydney, NSW.

18 Bowman, D.M., Williamson, G.J., Price, O.F., Ndalila, M.N. and Bradstock, R.A., 2021. Australian forests, megafires and the risk of dwindling carbon stocks. *Plant, Cell & Environment*, *44*(2), pp.347-355.

19 Bowman, D.M.J.S., Williamson, G.J., Gibson, R.K. et al. (2021) The severity and extent of the Australia 2019–20 Eucalyptus forest fires are not the legacy of forest management. *Nat Ecol Evol* 5, 1003–1010.

20 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

21 Lindenmayer, D.B., Zylstra, P., Kooyman, R. et al. (2022). Logging elevated the probability of high-severity fire in the 2019–20 Australian forest fires. *Nat Ecol Evol* 6, 533–535.

22 Wilson, N., Bradstock, R. and Bedward, M. (2022). Disturbance causes variation in sub-canopy fire weather conditions, *Agricultural and Forest Meteorology*, Volume 323, 2022, 109077, ISSN 0168-1923

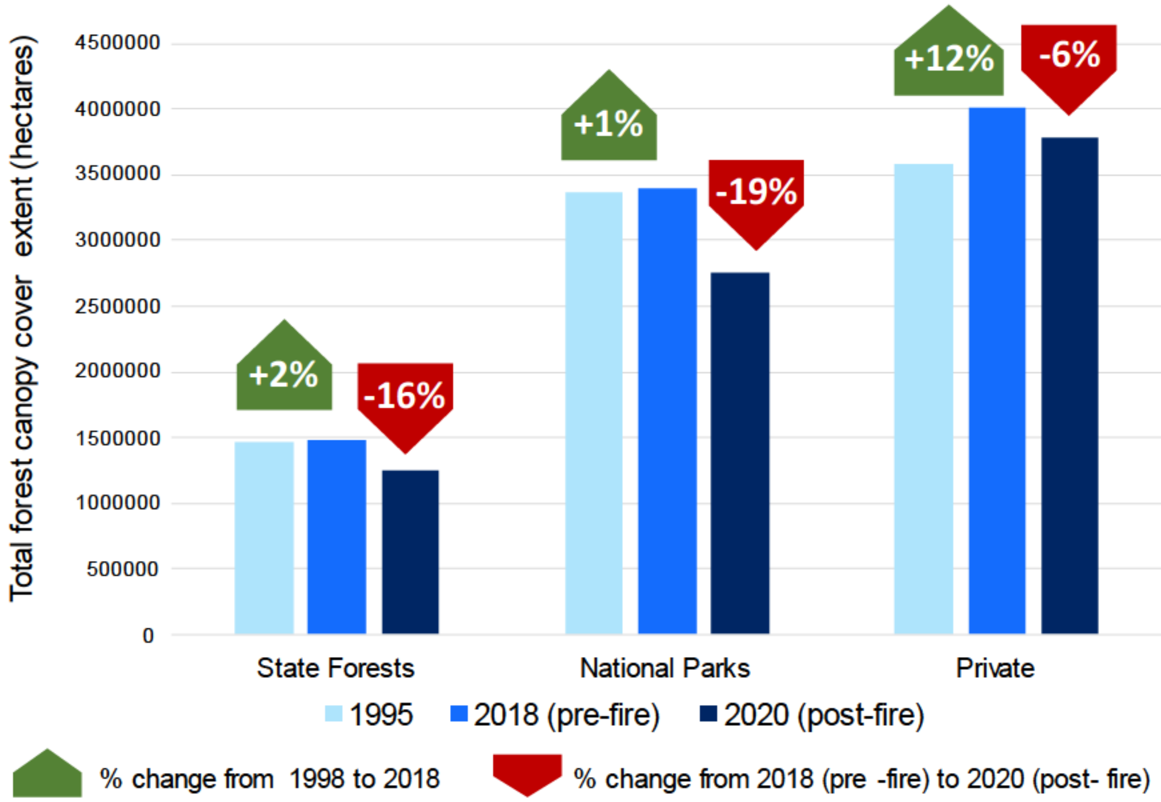

Figure 8: Change in forest canopy cover extent across NSW Regional Forest Agreement regions[23]

Despite the significant impacts on forest canopy cover, NSW forests have already started to recover and regenerate. A study monitoring vegetation recovery across NSW after the 2019-20 wildfires has observed that over 75 percent of burned areas in sub-tropical bioregions in north-east NSW already had greater than 80 percent spectral recovery after one year.[24] This study found that post-fire recovery generally aligned with regional climate and productivity, with better rates of recovery in warmer areas with conditions more conducive to fast growth and slower recovery in alpine and montane bioregions with cold climates and slower growth rates.[25]

23 Natural Resources Commission - NSW Government (2022): NSW Forest Monitoring and Improvement Program RFA Historic Forest Cover Extent - 1995 to 2019. Version 1.0. Terrestrial Ecosystem Research Network. (Dataset).

24 Gibson, R.K. and Hislop, S. (2022), Signs of resilience in resprouting Eucalyptus forests, but areas of concern: 1 year of post-fire recovery from Australia's Black Summer of 2019–2020, *International Journal of Wildland Fire* doi:10.1071/WF21089

25 *Ibid.*

Forest carbon and carbon emissions

The 2019-20 fire season also resulted in significant carbon emissions from NSW coastal forests, including:

- around 90 million tonnes of forest biomass carbon released to the atmosphere
- around 63 million tonnes of carbon moving from the living to dead organic matter pools.[26]

Figure 9 emphasises the magnitude of this event compared with releases in other years within the assessment period.

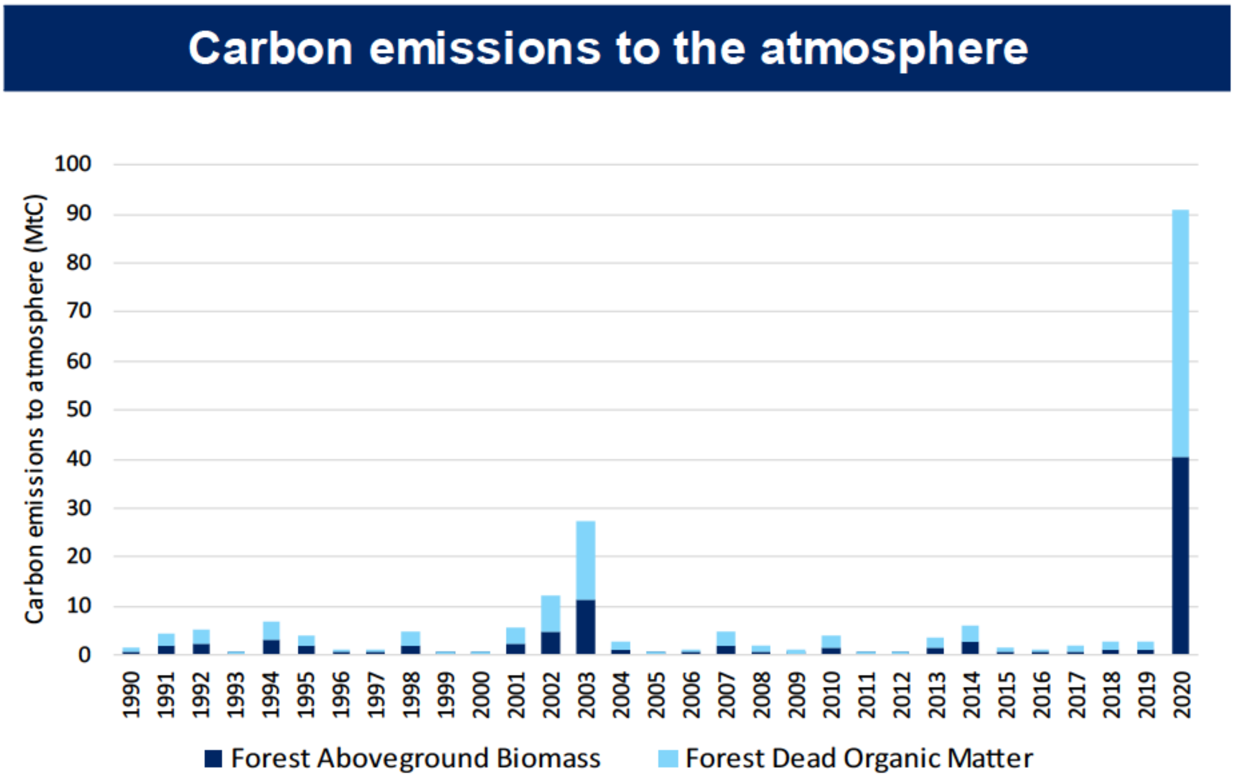

Figure 9: Movements of carbon from forest aboveground biomass and dead organic matter to the atmosphere as a result of the 2019-20 fire season[27]

Overall, considering all gains and losses of carbon over the period 1990 to 2020, the forest carbon stock[28] in NSW is now estimated to be 164 million tonnes less in 2020 than in 1990 (a decrease of around 7 percent).[29] A significant amount of the carbon emitted during the wildfires is expected to be recaptured as the forests recover. However, the extent to which these emissions are fully offset by vegetation regrowth depends on the capacity of the affected forests to recover and the potential impact of subsequent disturbances. **Sections 1.3.2, 1.4.3** and **2.2** explore these issues in more detail.

26 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

27 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

28 Note: this figure includes aboveground biomass, belowground biomass, dead organic matter, and harvested wood products in use. Soil carbon and harvested wood products in land fill were not included in this result.

29 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

The regional variation in change in forest carbon following the fires in 2020 compared with the 1990 baseline is shown in **Figure 15**, with the largest losses in the south coast and alpine regions (see **Sections 0** and **1.5** for more discussion on regional differences).

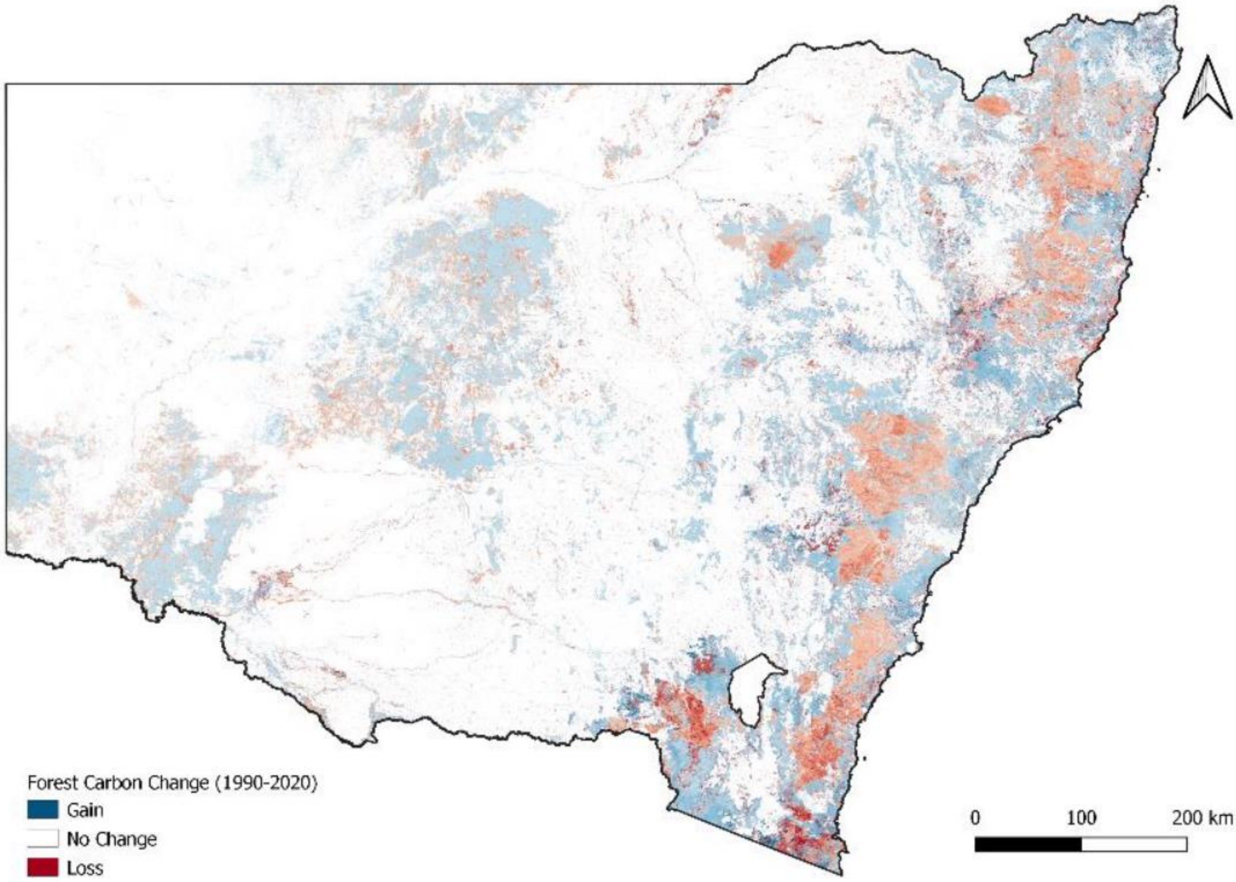

Figure 10: Spatial Output of change in forest carbon within NSW between 1990 and 2020, including above ground biomass, below ground biomass, and dead organic matter. Harvested wood products in use and soil carbon are not included[30]

Soil organic carbon

The impact of major wildfire events on soil organic carbon levels is also significant and subject to longer recovery periods than forest carbon stocks. Although soil sampling data from areas burnt in the 2019-20 fires is not yet available, FMIP-funded modelling predicts that the potential loss of soil organic carbon immediately following a wildfire event ranges between 40 and 60 percent (**Figure 11**).[31] The Commission cautions that this modelling does not represent the predicted loss of soil organic carbon from the 2019-20 fires. It does, however, give an insight into the potential impacts of wildfire by calculating the theoretical loss of soil organic carbon if forested areas in the Regional Forest Agreement region were burnt with a uniform intensity fire.

30 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

31 Moyce, M.C.; Gray, J.M.; Wilson, B.R.; Jenkins, B.R.; Young, M.A.; Ugbaje, S.U.; Bishop, T.F.A.; Yang, X.; Henderson, L.E.; Milford, H.B.; Tulau, M.J. (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry and Environment and University of Sydney.

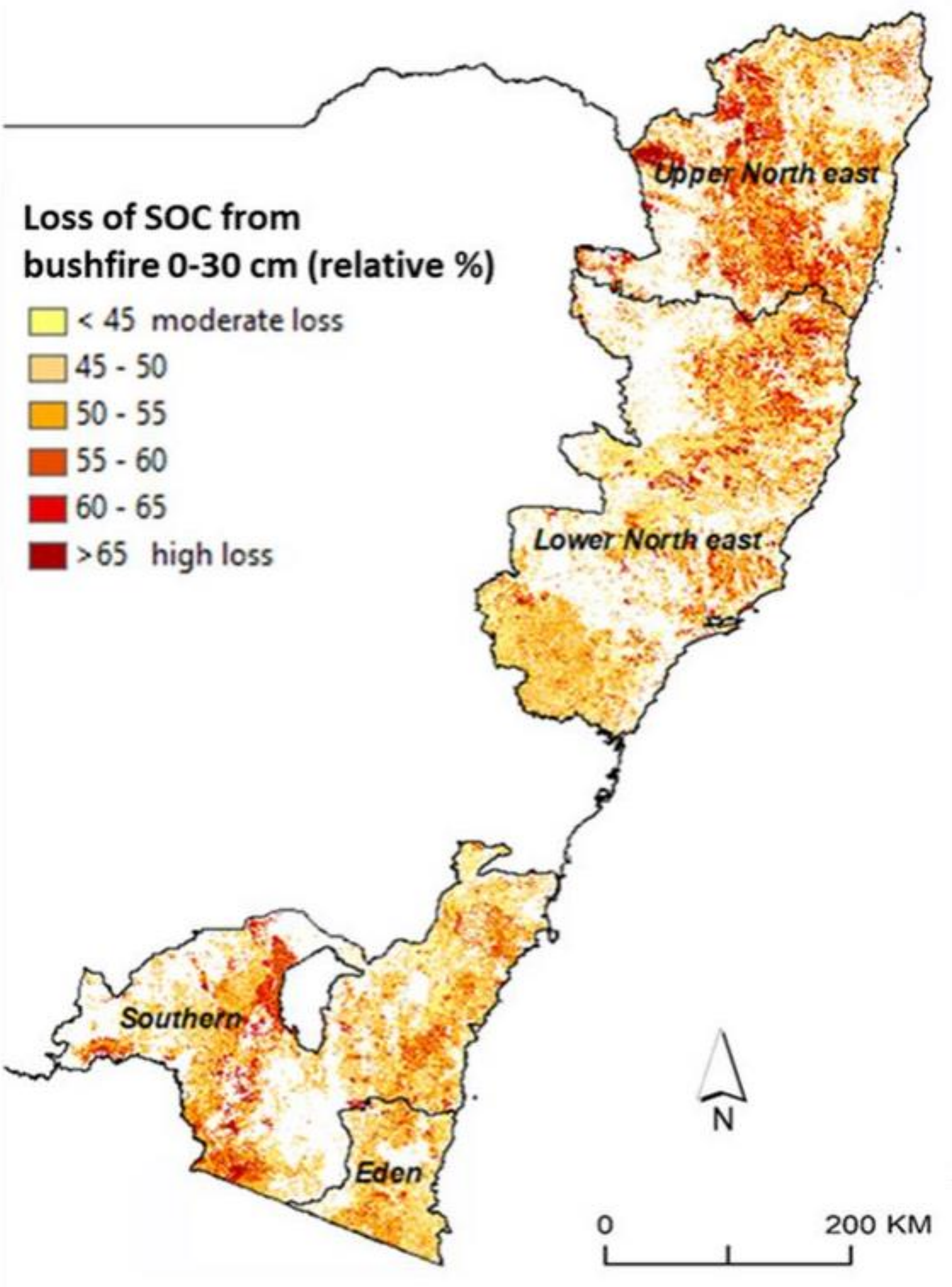

Figure 11: Predicted relative change (percentage) in surface soil organic carbon (SOC) concentrations immediately following a wildfire event[32,33]

Post-fire recovery of soil organic carbon was estimated to be around 60 percent after 20 years, with full recovery after around 75 years. These recovery estimates do not account for additional bushfires during this time, and there is a risk that some areas could enter a cycle of declining soil organic carbon if subjected to repeated fire events and/or other disturbances such as grazing, timber harvesting or land clearing.

32 Model was run with the variable representing the number of years since bushfire (wildfire) set to the immediate aftermath of bushfire hypothetically applied across the entire RFA study region.

33 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry and Environment and University of Sydney.

Biodiversity and species habitat

The 2019-20 fires also had extensive impacts on the habitat of hundreds of species (**Figure 12, Figure 13**). Research indicates that fire events are an important driver in species occupancy for many flora and fauna species across coastal NSW, including hundreds of flora species identified as being fire responsive, some of which are associated with long-unburnt sites.[34]

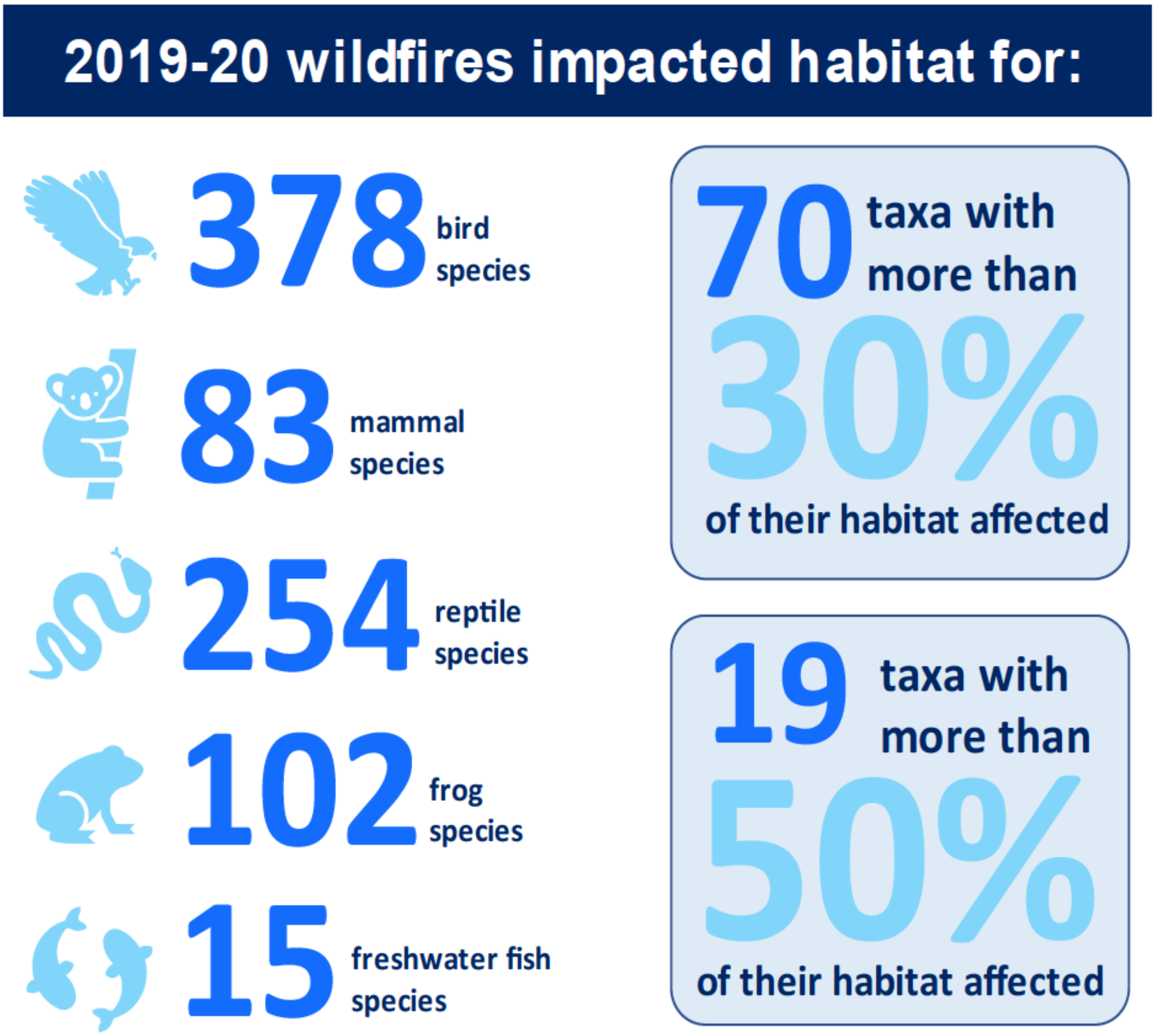

Figure 12: Species with habitat impacted by the 2019-20 fire season[35]

34 Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW FMIP

35 Ward, M., Tulloch, A.I.T., Radford, J.Q., Williams, B.A., Reside, A.E., Macdonald, S.L., Mayfield, H.J., Maron, M., Possingham, H.P., Vine, S.J., O'Connor, J.L., Massingham, E.J., Greenville, A.C., Woinarski, J.C.Z., Garnett, S.T., Lintermans, M., Scheele, B.C., Carwardine, J., Nimmo, D.G., Lindenmayer, D.B., Kooyman, R.M., Simmonds, J.S., Sonter, L.J. and Watson, J.E.M. (2020). Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature, Ecology and Evolution*. 4: 1321–1326.

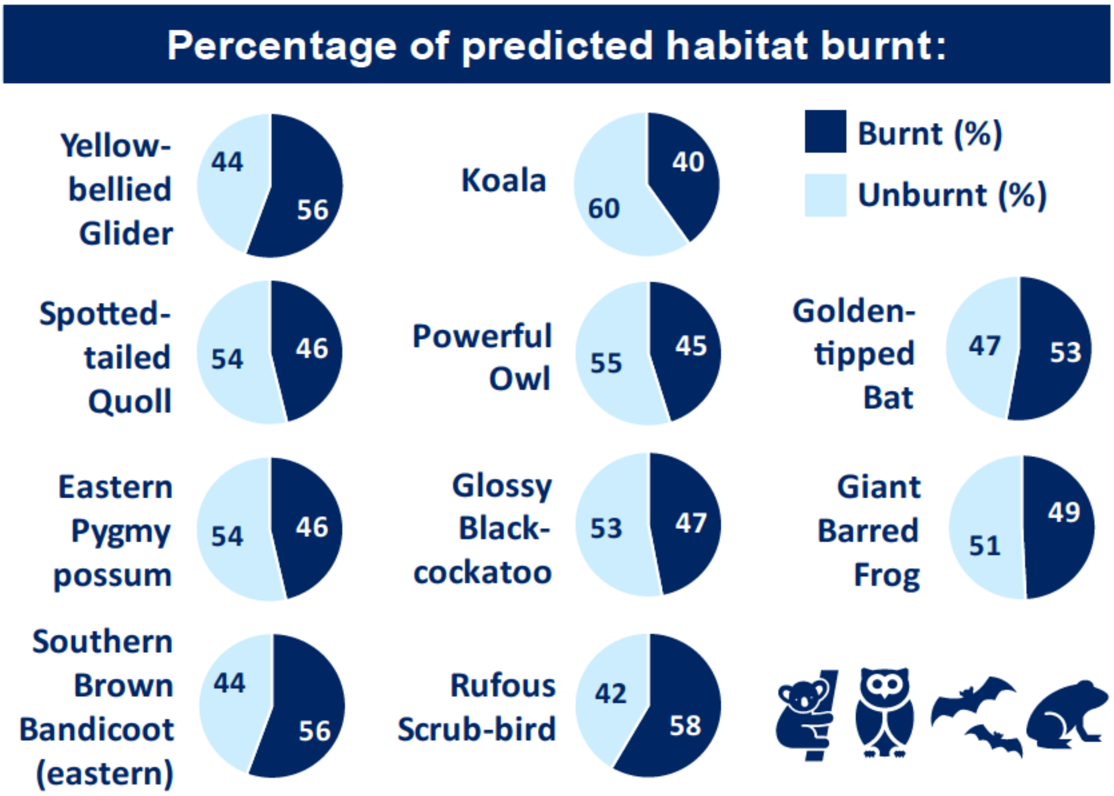

Figure 13: Percentage of predicted habitat burnt in 2019-20 for species in forested Coastal IFOA areas[36]

The FMIP also funded research into the impact of the 2019-20 wildfires on koalas and their habitat across north-eastern NSW.[37] For local koala populations, declines in koala density were observed in areas with a greater extent of medium or high fire severity. Koalas were temporarily absent in some areas where high fire severity dominated the landscape, although surveys one year after the fires showed koalas were returning to these areas. In contrast, in unburnt or predominantly low fire severity areas, koalas continued to be widespread, with little to no signs of decreased local population density post-fire compared with pre-fire local population density. At the regional scale, the broader population[38] of koalas across north-east NSW has been resilient to the 2019-20 wildfires, with no initial decline in post-fire occupancy detected.

Following the fires, only 10 percent of forests in coastal NSW are within their recommended fire frequency thresholds, with large areas at higher risk of a loss of plant diversity.[39] There have been significant increases in the proportion of area in the 'vulnerable' and 'too frequently burnt' categories that indicate a risk of decline in plant diversity (**Figure 14)**. Half of the state forest and national park area in coastal NSW is now classified as 'vulnerable', meaning the 2019-20 fires effectively doubled the extent of vulnerable forested vegetation on these tenures.

36 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

37 Natural Resources Commission (2022), *Summary paper - koala and habitat response after the 2019-20 wildfires*, prepared for the NSW Forest Monitoring and Improvement Program.

38 Also referred to as the metapopulation, which is a group of separate but interacting populations (also known as subpopulations) that are distributed across a region.

39 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

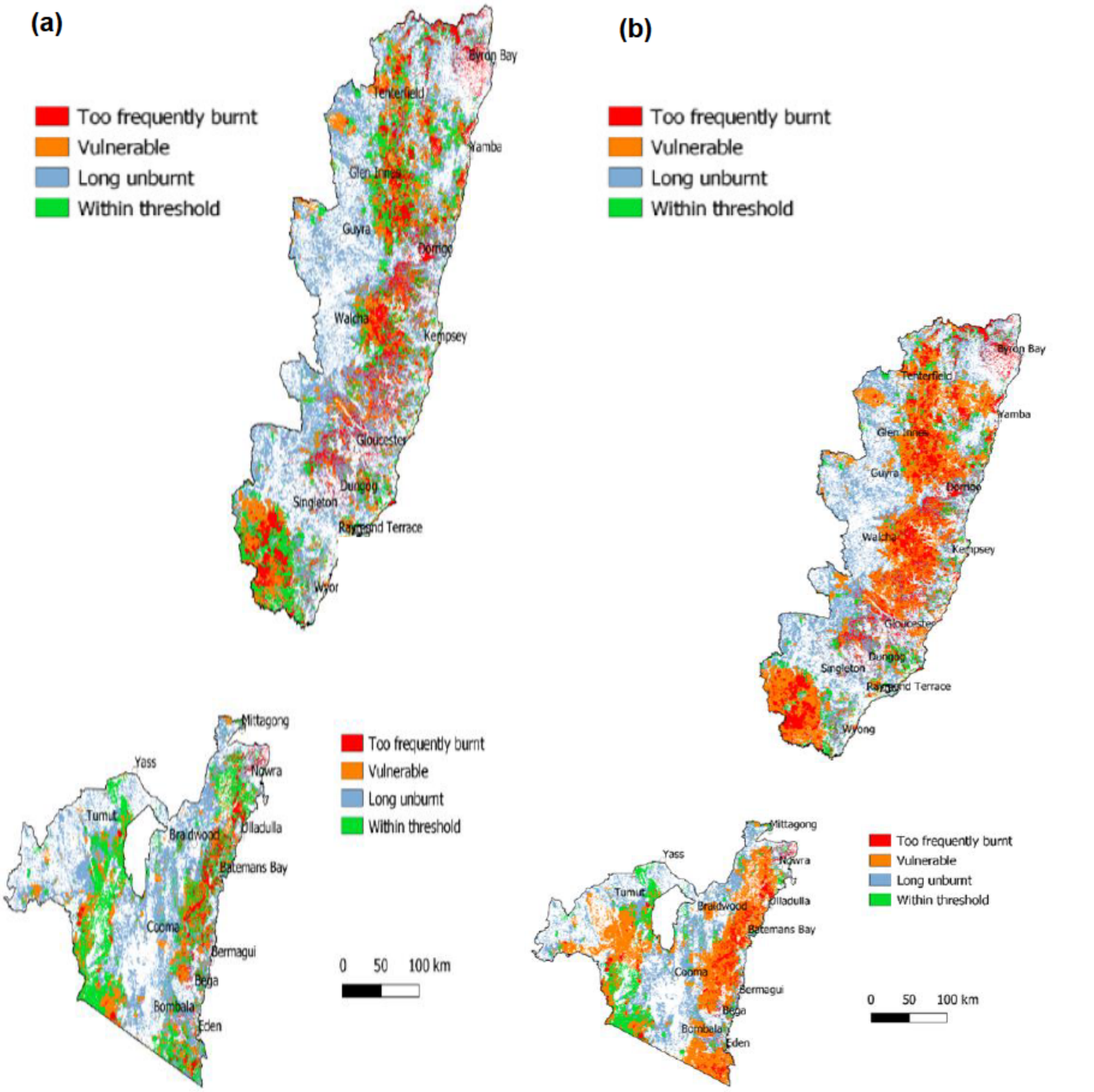

Figure 14: The status of 'threshold' categories indicating plant biodiversity responses to fire frequency across the Coastal IFOA area in (a) mid-2019 and (b) following the 2019-20 fires[40]

40 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

1.2.1 2019-20 wildfires were more intense in southern coastal NSW

In terms of the spatial distribution of impacts, the fires were more intense in southern coastal NSW than in northern coastal NSW, reducing the overall forest canopy cover extent in the south to well below 1995 baseline levels and releasing almost twice as much forest carbon (**Figure 15**).

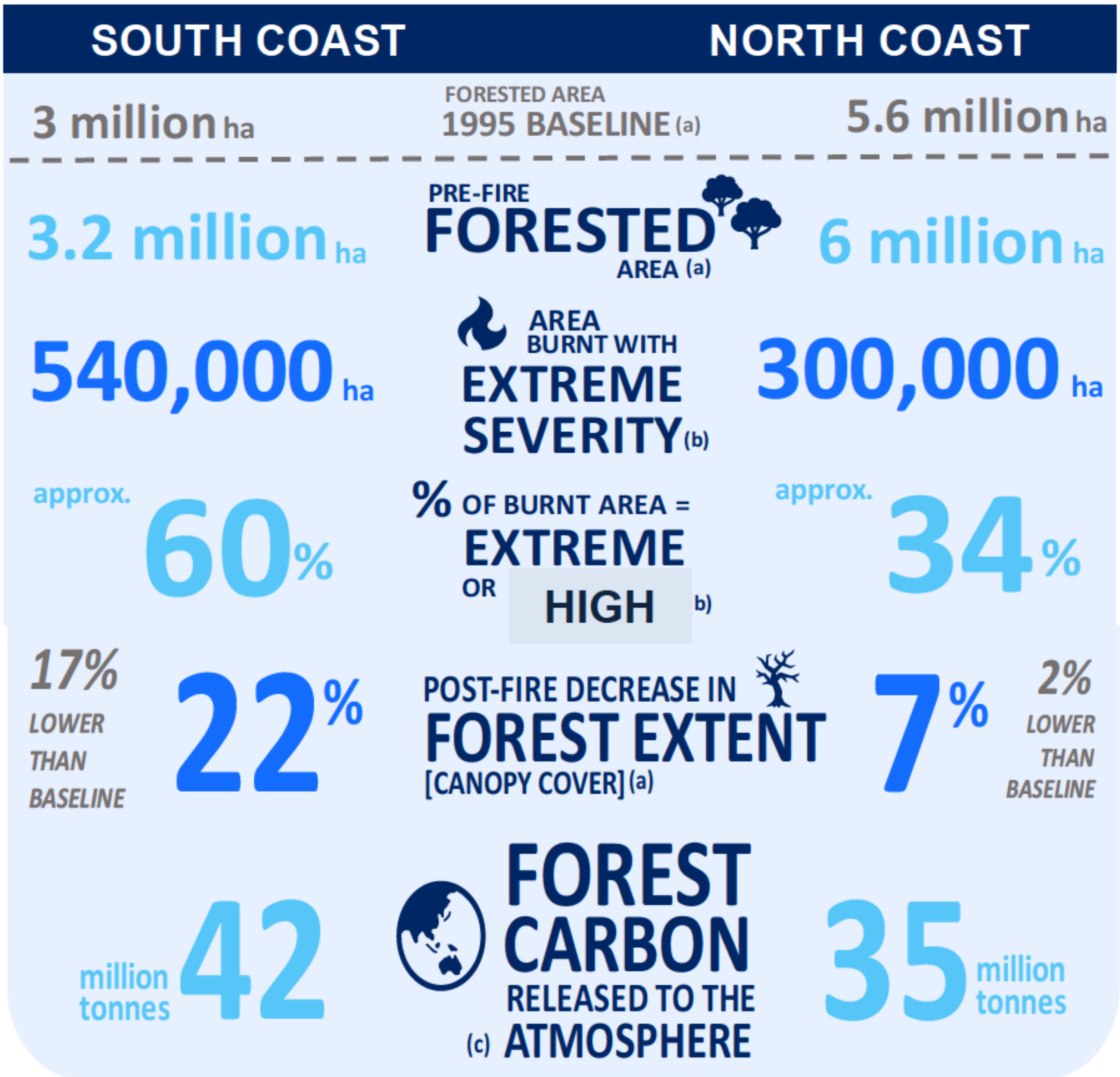

Figure 15: Comparison of impacts from the 2019-20 wildfires on the south and north coast [41]

[41] (a) Natural Resources Commission - NSW Government (2022): NSW Forest Monitoring and Improvement Program Historic Forest Cover Extent - 1995 to 2019 for RFA regions. Version 1.0. Terrestrial Ecosystem Research Network. (Dataset). https://doi.org/10.25901/sayz-pb50
(b) 2019-20 wildfire severity mapping available at https://datasets.seed.nsw.gov.au/dataset/fire-extent-and-severity-mapping-fesm
(c) Natural Resources Commission - NSW Government (2022): NSW Forest Carbon Stock - Aboveground, Belowground and Dead Organic Matter Carbon Mass 1990-2020. Version 1.0.0. Terrestrial Ecosystem Research Network. (Dataset). https://doi.org/10.25901/1qm2-8b33N. **Note:** these figures are for the northern and southern parts of the Regional Forest Agreement area. An additional 14 million tonnes of emissions related to the 2019-20 wildfires occurred outside the Regional Forest Agreement area.

1.2.2 Wildfires affected socio-economic values

Alongside impacts on ecological values, there have also been well-documented socio-economic impacts associated with the 2019-20 wildfires for both local communities and industries.[42] This includes the loss of 26 lives, along with the loss of 2,476 homes, other property and infrastructure, and livestock.[43] There was widespread disruption due to evacuations and significant community resources and organisation required for volunteer firefighting efforts.

There were also impacts on physical and mental health, air quality and drinking water, local industries and tourism. In January 2020, Canberra measured the worst air quality index of any major city in the world due to fine particle air pollution generated by the NSW wildfires.[44] This has the potential to directly impact human health even during relatively short exposures.

Some large tourism operators in the NSW Blue Mountains region had all bookings cancelled at the height of the wildfires in early 2020. Overall, tourist visitation declined by 40 percent from 2019 due to the combined effects of wildfires, extreme floods and COVID. An estimated 600 jobs were lost, with $118 million lost in direct revenue to the tourism industry.[45]

The 2019-20 wildfires led to a significant short-term reduction in wood supply (**Figure 16**) and short-term projected sustainable yields across the coast, particularly on the south coast. Of the 1.2 million hectares of forested State Forest area under the Coastal IFOA, 59 percent was burnt, almost half of which burnt at high or extreme severity.[46] A *force majeure* was declared for many wood supply agreements in both the south and north coast IFOA regions, and forestry operations ceased. Forestry operations resumed in early 2020, at first under site specific operating conditions[47] and subsequently under voluntary measures[48].

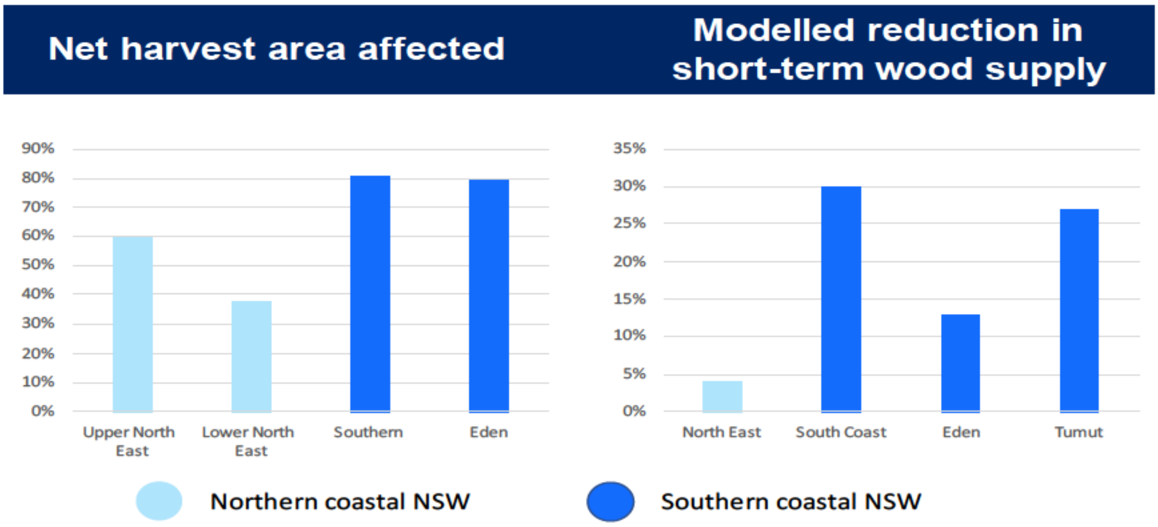

Figure 16: Overview of fire impact on net harvest area[49] and short-term wood supply[50]

42 NSW Department of Premier and Cabinet (2020), *Final Report of the NSW Bushfire Inquiry*, Sydney, NSW.
43 *Ibid.*
44 UN Environment Programme – The impacts of the Australian bushfires. Accessed at https://www.unep.org/news-and-stories/story/ten-impacts-australian-bushfires
45 REMPLAN (nd) Tourism Industry Profile 2021 Blue Mountains City Council
46 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW
47 See EPA website for further details.
48 See Forestry Corporation of NSW website for further details.
49 Forestry Corporation (2020). *Impact of fires 2019-20.* Website Available at: https://www.forestrycorporation.com.au/operations/fire-management/fire-impact-of-2019-20
50 Forestry Corporation of NSW (2020). *2019–20 Wildfires NSW Coastal Hardwood Forests Sustainable Yield Review*. Available at: 2019–20 Wildfires (nsw.gov.au)

Timber production was most significantly affected in the South Coast and Eden subregions (
Table 1). This is attributed to the greater extent and severity of fire on the south coast, as well as the lack of plantation resources to supplement harvesting of native forests in this region. In contrast, loss of supply of high quality logs from native forests on the north coast was offset by early harvesting of hardwood plantations.

The reductions in wood supply from the 2019-20 wildfires had flow-on impacts to the forest industry in affected regions, including forest operations, log haulage, timber processing, and allied services. Employees in these fields are reported to have experienced reductions in work shifts and redundancies, with a stand down of 74 harvest and haulage jobs and 6 sawmill jobs reported in March 2021.[51]

Table 1: Change in high quality log supply in 2020 compared to average of preceding five years[52]

Subregion	Actual wood supply reduction in 2020 vs. average of preceding five years	
	Reduction in high quality supply	Notes
South Coast	-84% (16 / 84)	▪ Down from 47,225 to 7,545 cubic metres ▪ Primarily spotted gum ▪ Tablelands species harvest was extremely limited (less than 200 cubic metres harvested)
Eden	-93% (7 / 93)	▪ Down from 19,505 to 1,380 cubic metres ▪ Primarily silvertop ash ▪ Pulpwood supply also fell by 75 percent
Tumut **high quality alpine ash*	-2% (2 / 98)	▪ Limited change in alpine ash supply from 22,510 to 22,155 cubic metres ▪ Production supplemented by fire salvage operations
North Coast	-19% (19 / 81)	▪ Down from 256,500 to 207,830 cubic metres ▪ Native forest supply reduced by 58 percent, but supply was supplemented by plantation harvest ▪ Blackbutt availability increased due to plantation harvesting, but north coast spotted gum supply fell by 92 percent and blue gum, tallowwood and brush box decreased by 35 percent.

% Expected high quality supply delivered
% Reduction compared with previous 5 years

51 [NSW Government Budget Estimates 2020-2021, Supplementary Questions, Portfolio Committee No. 4 – Industry, Deputy Premier, Regional NSW, Industry and Trade]. Hearing: Friday 26 February 2021; Answers due by: 24 March 2021.
52 Forestry Corporation of NSW production data.

1.2.3 Post-fire surveys highlighted gaps in the understanding and management of Aboriginal cultural values

The 2019-20 wildfires had significant impacts on Aboriginal cultural values within NSW forests, including damage to cultural value sites and artefacts and preventing access and/or cultural practices in some areas. For example, post-fire site assessments for Aboriginal cultural values carried out as part of the FMIP identified burnt scar trees and areas where stone artefacts have been made brittle or exposed to erosion risks.[53] Aboriginal people were concerned that cultural sites will be deregistered or devalued in these cases where tangible cultural values are damaged or lost.

Positively, priority sites were able to be actively protected on Aboriginal managed lands and other key sites on other tenures (including rock art and bora grounds) were reported to be unaffected. The post-fire site visits also allowed for continuation of cultural obligations to Country and revealed cultural values, including scar trees, artefact scatters and cultural resource sites, that had been previously inaccessible due to vegetation.

An overarching finding of the case studies was that, with the exception of Aboriginal managed lands, Aboriginal cultural values were poorly understood and managed across all tenures during the fire event. Aboriginal people also reported a general lack of access to cultural sites and barriers to carrying out cultural practices or caring for Country, particularly on private land. As such, there is a need to improve Aboriginal peoples' involvement in land management and decision making – including the identification, management, and monitoring of cultural values.

1.3 NSW forests are currently vulnerable and under pressure

NSW forests are already under stress from the impacts of the 2019-20 wildfires, increasing their vulnerability to future disturbances that are expected to occur with increasing frequency and severity. In addition, existing threats, such as invasive species and habitat loss and degradation continue to impact forest values in NSW forests.

1.3.1 Fire-affected areas are at higher risk during the post-fire recovery phase

Research indicates that, in general, eucalypts are highly resilient to fire, with the forest canopy expected to recover over time following a wildfire.[54] As mentioned in **Section 1.2**, a study has confirmed vegetation recovery is already underway in fire-affected areas, particularly in sub-tropical bioregions in north-east NSW.[55]

However, during the post-fire recovery phase forest health and condition are impacted and short-term losses of potential suitable habitat – including hollow bearing trees, nesting and food resources – are expected for many priority threatened species.[56] Further, the size and intensity of the 2019-20 fires, along with impacts from harvested areas, means refugia availability and habitat connectivity are likely to have been affected across the broader landscape.

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53 Firesticks Alliance Indigenous Corporation (2022), *Aboriginal Cultural values and renewal in NSW forests post-wildfires - Synthesis report*, Firesticks Alliance Indigenous Corporation.

54 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

55 Gibson, R.K. and Hislop, S. (2022), Signs of resilience in resprouting Eucalyptus forests, but areas of concern: 1 year of post-fire recovery from Australia's Black Summer of 2019–2020, *International Journal of Wildland Fire* doi:10.1071/WF21089

56 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

Forest regeneration and seed banks may also be impacted, particularly given the extreme nature of the 2019-20 fire event, which can have medium- to long-term consequences for species habitat and recolonisation. Regeneration can also be adversely affected if additional fire events occur in burnt areas that are still recovering. Affected areas are therefore considered particularly vulnerable to impacts from subsequent disturbances such as timber harvesting or fire in the next 5 to 10 years while burnt forested areas recover and regenerate.[57]

Critically, in some places the severity of the fires was such that the recovery period may be lengthy, and ability to achieve full recovery for forest condition and fauna occupancy is uncertain. For example, there may be small areas of forest loss where intense fire in particular forest types results in the conversion of previously forested areas to a non-forest vegetation type, such as woodland or grassland. The Australian Alps bioregion has been identified as an area of particular concern due to a low rate of vegetation recovery observed post-fire.[58]

Recently, coastal NSW has also experienced a series of extreme rainfall events in the period between 2020 and 2022, resulting in widespread and severe flooding in many areas. These events are likely to have had mixed outcomes in the context of NSW forests, with heavy rainfall and flooding further impacting socio-economic, soil and water values in areas that were already affected by fire. However, the increased rainfall and flooding are also expected to contribute to accelerated regeneration of fire-affected vegetation in some areas.

1.3.2 Forest recovery post-fire has implications for carbon balances

It is a commonly used assumption in carbon accounting that the forest carbon lost due to fire will be reabsorbed by the forests as they recover and regenerate in the 10-15 years post-fire.[59] However, the extent to which the forests are able to recapture the lost carbon depends on the capacity of the forests to fully recover post-disturbance, along with the absence of subsequent disturbances in the recovery period.

As highlighted in the previous section (**Section 1.3.1**), there is concern that increasingly frequent and severe droughts and fires are undermining forests' ability to fully recover after these events. Poor forest recovery is likely to reduce the amount of carbon able to be stored by the forest, resulting in net carbon emissions.[60] Similar cycles of decline relating to long post-fire recovery periods and shorter intervals between disturbance events have also been identified as a risk for soil organic carbon (see **Section 1.2**).

Projected changes in climate and fire regimes in future – including shorter recovery intervals between disturbance events – may further exacerbate this issue (see **Section 1.4**). A recent study indicates that burnt area and frequency of megafires is already increasing, with decreases in the mean number of years since the last fire observed over the last four decades.[61]

The potential shift towards reduced carbon storage and increased carbon emissions from NSW forests over time is important in the context of Government commitments to achieve net zero carbon emissions by 2050. Opportunities to better understand and manage the carbon balance of NSW forests to try and mitigate these risks are discussed in **Section 2.2**.

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57 *Ibid.*

58 Gibson, R.K. and Hislop, S. (2022), Signs of resilience in resprouting Eucalyptus forests, but areas of concern: 1 year of post-fire recovery from Australia's Black Summer of 2019–2020, *International Journal of Wildland Fire* doi:10.1071/WF21089

59 Australian Government (2020), *Estimating greenhouse gas emissions from bushfires in Australia's temperate forests: focus on 2019-20*, Australian Government Department of Industry, Science, Energy and Resources.

60 Bowman, D.M., Williamson, G.J., Price, O.F., Ndalila, M.N. and Bradstock, R.A., 2021. Australian forests, megafires and the risk of dwindling carbon stocks. *Plant, Cell & Environment*, *44*(2), pp.347-355.

61 Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J., Pepler, A. and Haverd, V., 2021. Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature communications*, 12(1), pp.1-11.

1.3.3 Other threats and drivers of change affecting NSW forests

While the unprecedented 2019-20 wildfires caused the largest step changes in forest indicators during the assessment period, other factors – such as loss and degradation of habitat and invasive species – pose an ongoing threat to biodiversity and forest values.[62]

Habitat loss and degradation

Habitat loss and degradation can arise as a result of anthropogenic disturbances such as vegetation clearing and land-use change, timber harvesting and grazing.

The impacts of vegetation clearing and land-use change resulting in permanent habitat loss are well known.[63] While the *NSW 2021 State of the Environment* report reported a decline in primary forest clearing[64] since 1990, secondary forest clearing (clearing of regrowth) was identified as an ongoing issue.[65] For example, cleared areas were estimated to have been greater than areas of regrowth in more than half of the last 14 years. The legacy of past clearing continues to impact the function of forest ecosystems including habitat for fauna.[66] Forest clearing also leads to a shift from living biomass to dead organic matter and eventual loss to the atmosphere, impacting the carbon cycle and net emissions.[67]

Timber harvesting generally results in local, short-term impacts on habitat followed by forest recovery and regeneration, with different silviculture types having greater or lesser impacts. FMIP analysis shows that at the state scale, timber harvesting within NSW is a comparatively minor disturbance type in comparison to other sources of forest cover loss (**Figure 17**).[68]

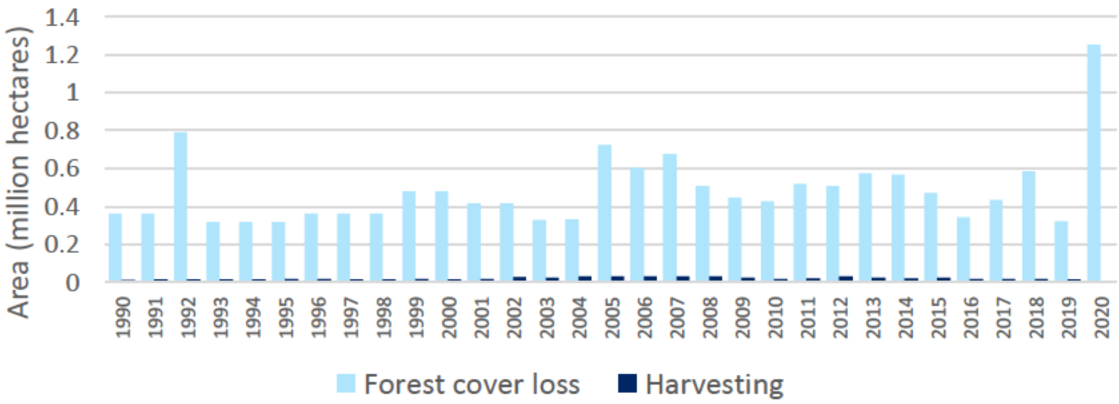

Figure 17: **State-wide comparison of the area of forest cover loss in comparison with area harvested (excluding plantations)**[69]

62 Commonwealth of Australia (2021) *Australia State of the Environment 2021*, Commonwealth of Australia, Canberra, ACT

63 Department of Planning and Environment, https://www.environment.nsw.gov.au/topics/animals-and-plants/threatened-species/nsw-threatened-species-scientific-committee/determinations/final-determinations/2000-2003/clearing-of-native-vegetation-key-threatening-process-listing

64 Land which has been a forest since 1972

65 NSW Environment Protection Authority (2021), *NSW State of the Environment 2021*, State of NSW and the NSW Environment Protection Authority

66 Australia State of the Environment Report 2016, https://soe.environment.gov.au/

67 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry and Environment and University of Sydney.

68 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

69 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, NSW Natural Resources Commission, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

Appropriate rule sets, including areas permanently excluded from harvesting, can effectively distribute the impacts of timber harvesting in space and time.[70] However, species occupancy analysis identified relationships between harvesting and impacts on the distribution of some fauna species.[71] Further, this study identified nine rainforest and wet sclerophyll plant species that are likely to be sensitive to timber harvesting, noting that rainforest areas are excluded from harvesting under current protections.[72] There is also potential for cumulative impacts on forest recovery, habitat and water quality values in harvested landscapes that are also subject to fire.[73]

The impact of harvesting on forest carbon stocks is another consideration, with studies showing that sites subject to harvesting had lower carbon stocks than comparable undisturbed areas, particularly due to removal of large trees.[74]

Disturbance due to grazing activities in forests can also lead to ecosystem degradation. For instance, areas subject to increased ground disturbance, in particular forests in which grazing is permitted, were found to have lower concentrations of soil organic carbon and higher bulk density (suggesting poorer soil structure and condition) than less disturbed areas.[75]

Invasive species

According to the national *State of the Environment 2021* report, invasive species are the most common pressure on species listed under the *Environment Protection and Biodiversity Conservation Act 1999*.[76] FMIP species occupancy research highlighted feral cats and foxes as key pest species driving extinction processes, particularly for terrestrial mammals.[77] Introduced herbivores were also identified as a threatening factor for native species, such as rabbits, goats, pigs, cattle, horses and deer.[78]

A NSW National Parks and Wildlife Service fauna species monitoring program (WildCount) used remote cameras to monitor fauna in selected national parks and conservation reserves between 2012-2016. This monitoring program found that introduced species, particularly feral cats and foxes, were widespread across both northern and southern coastal forests. For example, feral cats and foxes were estimated to occur on every second monitoring site in southern NSW and

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70 Mori, A.S. and Kitagawa, R. (2014). Retention forestry as a major paradigm for safeguarding forest biodiversity in productive landscapes: a global meta-analysis. *Biological Conservation*. 175: 65-73.

71 Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program.

72 *Ibid.*

73 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

74 Roxburgh, S.H., Wood, S.W., Mackey, B.G., Woldendorp, G. and Gibbons, P. (2006), Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia. Journal of Applied Ecology, 43: 1149-1159. https://doi.org/10.1111/j.1365-2664.2006.01221.x

75 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program, Final report v1.1* for NSW Natural Resources Commission by NSW Department of Planning, Industry and Environment and University of Sydney.

76 Commonwealth of Australia (2021) *Australia State of the Environment 2021*, Commonwealth of Australia, Canberra, ACT

77 Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program.

78 *Ibid.*

were determined to have the fourth and fifth highest occupancy, respectively, of mammal species in Southern and Eden region forests.[79]

Invasive weed species such as lantana and blackberry can also pose a risk to NSW forests by changing the structure and composition of forested areas, resulting in habitat and species loss. Lantana alone is listed as a threat to 96 threatened species, populations and ecological communities listed under the *Biodiversity Conservation Act 2016.*[80]

Ongoing issues around weeds and invasive species were also raised during a recent NSW Parliamentary Inquiry, particularly in relation to the management of weeds in forested areas such as state forests and softwood plantations.[81] The inquiry reported that forestry operations in state forests can result in infestations of weeds and other invasive species, often with significant costs to adjacent private landholders. The inquiry committee recommended a review of weed management to ensure all landholders contribute to coordinated weed control.

1.4 Recent natural disasters indicate a challenging future

Climate and climate-driven disturbances are expected to continue to lead to future changes in NSW forests. Climate across NSW is predicted to become more variable in the future, with periods of drought and intense rainfall both increasing, bringing heightened fire and flood risk.

Notably, impacts from climate related disturbances are often interlinked, such that one disturbance can exacerbate another, placing forests at even higher future risk. For example, droughts may increase the severity of fires and threaten the rate and vigour of regeneration and recovery after fires. Fires may also fundamentally change forest hydrology and/or exacerbate erosion impacts from intense rainfall. As such, the 2019-20 fire season provides an example of the kind of disturbance expected more frequently in future with a changing climate.[82,83]

1.4.1 Warmer climate, changing annual rainfall and more intense rainfall events

Higher temperatures, more hot days and increased evapotranspiration are forecast for the north and south coast in the near future (2020-39), with these trends strengthening in the far future (2060-79).[84,85] There is evidence that regional climate drivers (Indian Ocean Dipole and El Niño/Southern Oscillation) are intensifying and promoting cycles of intense biomass growth followed by drought.[86]

79 Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program.
80 NSW Environment Protection Authority (2021), *NSW State of the Environment 2021*, State of NSW and the NSW Environment Protection Authority
81 New South Wales Parliament (2022). *Report No. 54: long term sustainability and future of the timber and forest products industry*. Legislative Council, Portfolio Committee No. 4 – Customer Service and Natural Resources.
82 Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J., Pepler, A. and Haverd, V., 2021. Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature communications*, 12(1), pp.1-11.
83 Boer, M.M., Resco de Dios, V. and Bradstock, R.A., (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10(3), pp.171-172.
84 NSW Department of Planning, Industry and Environment (2021). *Draft Regional Water Strategy - North Coast*. At: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/354245/nc-strategy.pdf
85 NSW Department of Planning, Industry and Environment (2020). *Draft Regional Water Strategy - South Coast*. At: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0020/329015/draft-rws-sc-strategy.pdf
86 Alluvium (2020). *Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests*. Report for the Natural Resources Commission.

Two scenarios from the NSW and Australia Regional Climate Modelling (NARCliM) project have been used in recent research[87] commissioned under the Coastal IFOA monitoring program:

- a 'warmer/wetter' scenario88 modelling the lower limits of likely change to fire conditions
- a 'hotter/little change in rainfall' scenario89 representing more extreme conditions driven by increased temperatures without an increase in rainfall.

The range of maximum temperature rise between these two scenarios is between 0.4-1°C in the near future (2020-2039) and 1.8-2.6°C in the far future (2060-2079).[90]

In the near future, the increases in temperature are expected to be accompanied by a decrease in annual rainfall, particularly on the NSW south coast.[91] Conversely, in the long term, trends for annual rainfall are expected to shift again, with increased rainfall expected across much of the state. Areas within the Australian Alps and South Eastern Highlands bioregions are an exception, with projections showing long-term decreases in annual rainfall in both the near and far future.

Despite an expected decrease in total annual rainfall in the near future, intense rainfall events are expected to increase under climate change.[92,93] More short-duration intense rainfall events are likely due to increased convection and thunderstorms, with hourly rainfall intensities predicted to increase by around 20 percent for every degree of warming.[94] There is also potential for more frequent east coast lows and associated prolonged rainfall events and flooding due to intensification of El Niño/Southern Oscillation cycles.[95] There is already evidence that the intensity of short duration (hourly) extreme rainfall events has increased.[96] There is also some evidence emerging that rainfall systems may be starting to stall in one place for longer periods of time, leading to greater inundation in the affected area than would be expected based on previous patterns in rainfall system dynamics.[97]

87 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

88 MIROC3.2 ensemble projecting an increase in precipitation (wetter) and an increase in temperature (warmer)

89 ECHAM5 ensemble projecting a larger increase in temperature (hotter) with little change in precipitation (little change)

90 AdaptNSW NSW Climate Change Snapshot: https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/Climate-projections-for-your-region/NSW-Climate-Change-Downloads

91 State of NSW and Office of Environment and Heritage (2018). *Climate Change Impacts on Three Key Soil Properties in New South Wales - 2nd edition*. Sydney, NSW.

92 NSW Department of Planning, Industry and Environment (2021). *Draft Regional Water Strategy - North Coast*. At: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0005/354245/nc-strategy.pdf

93 NSW Department of Planning, Industry and Environment (2020). *Draft Regional Water Strategy - South Coast*. At: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0020/329015/draft-rws-sc-strategy.pdf

94 Alluvium (2020). *Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests*. Report for the Natural Resources Commission.

95 *Ibid.*

96 NSW Government (2022) *2022 Flood Inquiry Volume Two: Full report*, NSW Government, Sydney

97 *Ibid.*

1.4.2 Increasing fire risk and impacts

Climate change is expected to bring increased fire risk in the future – for example, increasing burned area, fire intensity and frequency of forest megafires – as drying climatic conditions are likely to favour more intense drying cycles that pre-condition catchments for major wildfire events.[98] [99] [100]These projections apply to both the north and south coast and indicate increased risks during both prescribed burning periods (spring) and the peak fire risk season (summer).[101] Recent research[102] used the 'warmer/wetter' and 'hotter/little change in rainfall' climate change scenarios (see **Section 1.4.1**) to predict how fire regimes and future fire weather in the NSW coastal area may change in the remainder of this century. This study showed that for most days the Forest Fire Danger Index (FFDI) under the current climate (1990-2009) had low to moderate fire danger scores, with progressively fewer days in higher fire danger categories. The current pattern of low to moderate fire danger is expected to continue under the 'warmer/wetter' climate change scenario. However, the 'hotter/little change in rainfall' scenario shows a strong shift towards higher fire danger conditions, becoming pronounced over the course of this century.

The potential effects of climate change on annualised expected area burned by wildfires were also assessed for each climate change scenario in the period 2060 to 2079 (**Figure 18**). The analysis relied on modelled case study landscapes that were chosen to represent conditions at the geographical limits of the southern and north-eastern regions covered by the Coastal IFOA.

As in the fire danger index review, the 'warmer/wetter' scenario shows minor reductions in area burnt. In contrast, the 'hotter/little change in rainfall' climate scenario shows a substantial increase in area burnt over time, with landscapes around the southeast corner of NSW and the Blue Mountains showing the widest scope for change and upper northeast NSW the least likelihood of change.

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98 Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J., Pepler, A. and Haverd, V., 2021. Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature communications*, 12(1), pp.1-11.

99 Boer, M.M., Resco de Dios, V. and Bradstock, R.A., (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10(3), pp.171-172.

100 King Karen J., de Ligt Robert M., Cary Geoffrey J. (2011) Fire and carbon dynamics under climate change in south-eastern Australia: insights from FullCAM and FIRESCAPE modelling. *International Journal of Wildland Fire* **20**, 563-577.

101 Office of Environment and Heritage (2014) *North Coast Climate change snapshot*. Sydney.

102 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

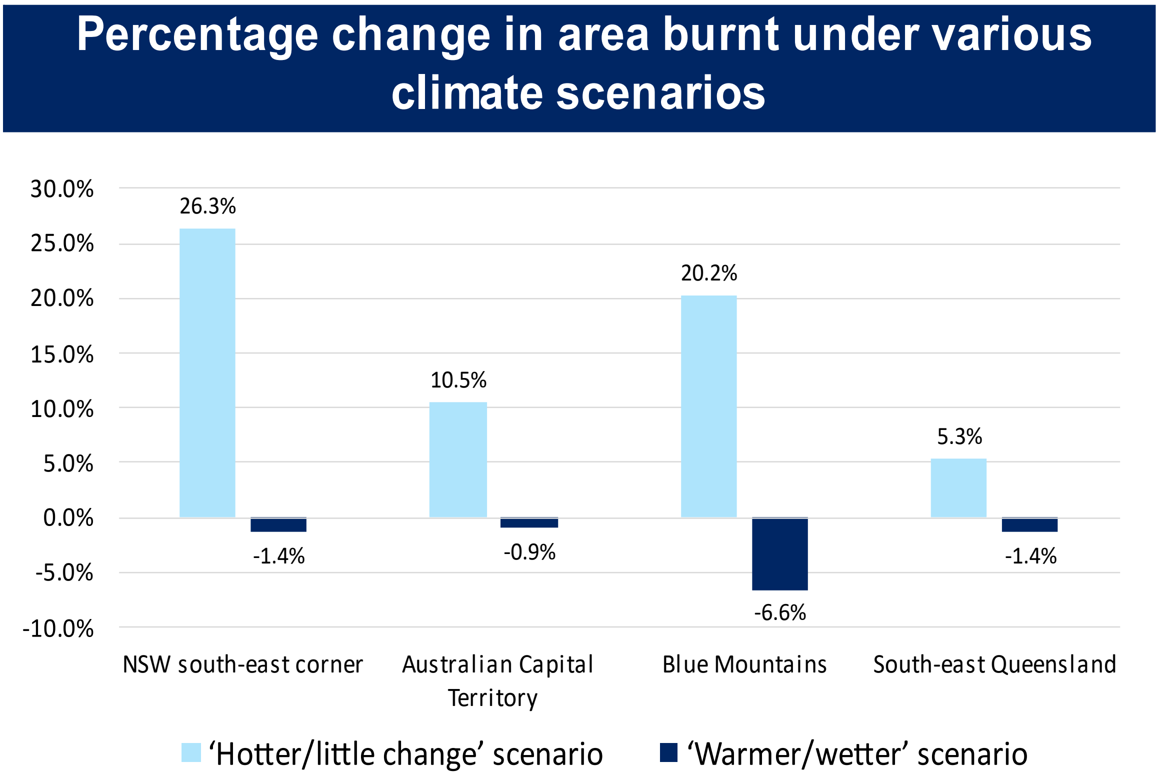

Figure 18: Simulated change in expected annual area burned by wildfire (approximate average) for selected landscapes under two far future climate scenarios (2060-2079)[103]

1.4.3 Impacts across forest indicators and values

Many of the FMIP research projects indicate there will be adverse impacts across a range of critical forest indicators under future climate and disturbance regime scenarios, including species habitat, forest carbon, soil organic carbon, soil alkalinity, and water quality.

Species habitat

The combined effects of climate change and fire represent the most significant threat to the biodiversity of eastern NSW forests.[104] Climate change is likely to affect species habitat through a range of mechanisms, including changing temperatures, soil pH, and shifts in the spatial and temporal distribution of food resources. Similarly, an increase in the frequency and severity of fires is likely to decrease the long-term availability and resilience of wildfire refugia and reduce the density of key habitat features such as large hollow-bearing trees and fallen logs.

Climate projections used as part of FMIP research into baselines, drivers and trends for species occupancy and distribution suggest that potential occupancy of 54 of 78 threatened fauna species will decline by 2070, with seven species[105] particularly impacted.[106] Fire – including variables such as years since fire and number of fires (or fire count) – was a primary driver or

103 *Ibid.*

104 Kavanagh,R., et al. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program.

105 Specifically the Rufous Bettong (*Aepyprymnus rufescens*), Rufous Scrub-bird (*Atrichornis rufescens*), Stuttering Frog (*Mixophyes balbus*), Barking Owl (*Nixox connivens*), Powerful Owl (*Ninox strenua*), Greater Glider (*Petauroides Volans*) and Sooty Owl (*Tyto tenebricosa*)

106 Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*. Report prepared for the Natural Resources Commission as part of the NSW Forest Monitoring and Improvement Program.

correlate for one quarter of all fauna species investigated and had a minor association with a further 11 percent of species modelled. Of the 81 climate-sensitive plant species identified, modelling predicted that 59 percent of species will have less medium to high-suitability habitat by 2070 due to climate change, whereas 37 percent will have more. Research into changing fire regimes in the Coastal IFOA area also found that suitable habitat was predicted to decline under projected 2030 and 2070 climate change scenarios for 14 of the 24 threatened fauna species assessed.[107]

If increases in fire extent and intensity are consistent with climate change forecasts, wildfire refugia will become increasingly important for the long-term viability of native forest-dependent plant and animal species. However, more extreme fire weather and/or drought in future may also undermine protection from fire currently offered by topographic position, context, or forest structure.[108,109] As a result, persistent fire refugia that have previously been sheltered from fire or experienced only low severity fires might be more likely to burn under changing fire regimes.[110] The 2019-20 wildfires already affected ecosystems that typically do not burn[111], including an estimated 8.6 percent of the 112,145 ha of rainforest in the Gondwana Rainforest of Australia World Heritage Area.[112,113]

Forest extent, forest carbon and carbon emissions

Disturbances such as drought and fire lead to a decrease in forest canopy cover extent and the release of forest carbon, both of which are expected to be mitigated to some extent by forest regrowth and recovery. However, as outlined in **Section 1.3.2**, forest recovery – and associated ecological value, long-term commercial viability and carbon sequestration – is at risk under predicted future climates.[114] Decreasing forest canopy cover extent and increasing forest carbon emissions may therefore become a more significant issue in future if forest recovery and regeneration in disturbed areas is undermined by repeated disturbances (see **Section 2.2** for further discussion of carbon emissions).

Soil organic carbon and alkalinity

In NSW, studies show soil organic carbon storage near the surface is strongly determined by climate, particularly water availability.[115] Climate change is predicted to contribute to a future decline in soil organic carbon over most forested areas in coastal NSW.[116]

107 Bradstock. R, Bedward, M., & Price, O. (2021), *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

108 Krawchuk, M.A., Meigs, G.W., Cartwright, J.M., Coop, J.D., Davis, R., Holz, A., Kolden, C. and Meddens, A.J.H. (2020). Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. *Frontiers in Ecology and the Environment*. 18: 235-244.

109 Nitschke et al. (2020). Spatial and temporal dynamics of habitat availability and stability for a critically endangered arboreal marsupial: implications for conservation planning in a fire-prone landscape. *Landscape Ecology* 35: 1553-1570.

110 Krawchuk, M.A., Meigs, G.W., Cartwright, J.M., Coop, J.D., Davis, R., Holz, A., Kolden, C. and Meddens, A.J.H. (2020). Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks. *Frontiers in Ecology and the Environment*. 18: 235-244.

111 NSW Department of Premier and Cabinet (2020), *Final Report of the NSW Bushfire Inquiry*, Sydney, NSW.

112 Nolan, R.H., Boer, M.M., Collins, L. Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B. and Bradstock, R.A. (2020). Causes and consequences of eastern Australia's 2019-20 season of mega-fires. *Global Change Biology.* 26: 1039-1041.

113 Peacock, R. J, and Baker, P.J. (2022) *Informing post-fire recovery planning of northern NSW rainforests*. Bushfire and Natural Hazards CRC, Melbourne.

114 Bowman, D.M., Williamson, G.J., Price, O.F., Ndalila, M.N. and Bradstock, R.A., 2021. Australian forests, megafires and the risk of dwindling carbon stocks. *Plant, Cell & Environment*, *44*(2), pp.347-355.

115 Hobley, E., Wilson, B., Wilkie, A., Gray, J. and Koen, T., 2015. Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. *Plant and Soil*, *390*(1), pp.111-127

116 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program, Final report v1.1* for NSW Natural

While the magnitude of decline in soil organic carbon varied between different climate model projections, the modelling indicates there will be an ongoing loss of soil organic carbon and associated soil condition (**Figure 19**). A mean relative loss of 17 percent is projected across the north coast, rising to over 37 percent relative loss in the south.

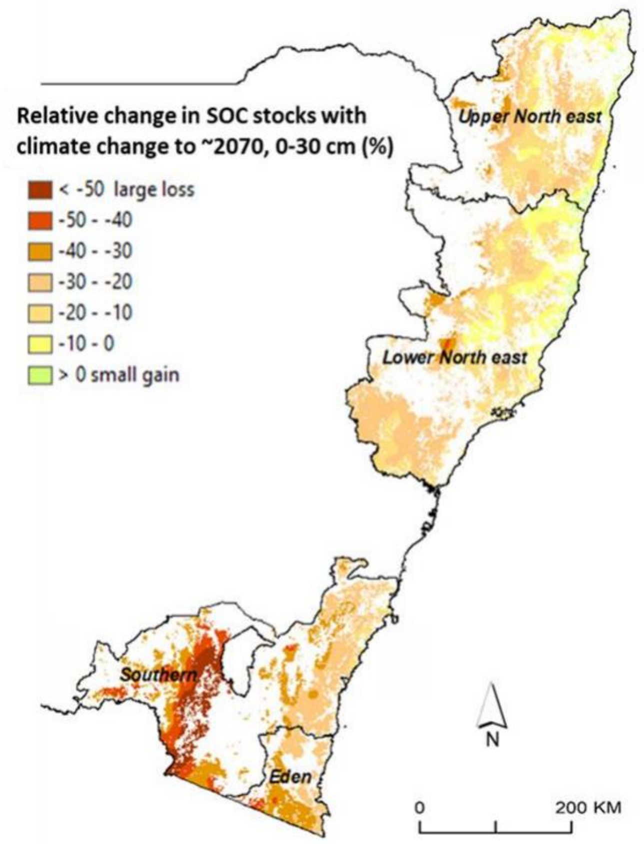

Figure 19: Predicted relative change (%) in surface soil organic carbon (SOC) concentrations with projected climate change to approx. 2070[117]

The greatest predicted losses in soil organic carbon are shown in areas with currently high soil organic carbon stocks, which has significant implications for carbon balances and government emissions targets. Highland regions, particularly in the southern Alps, are predicted to lose the largest quantity of soil organic carbon. As highlighted in **Section 1.2**, increased fire activity is likely to be a factor in this decline, as repeated disturbance events combined with long recovery periods will prevent soils from fully recovering organic carbon once lost.

Similar analysis for changes in soil pH in the same study[118] suggests a slight increase to more alkaline soils over coastal NSW by 2070. While these changes may seem minimal, any changes in soil pH may affect natural ecosystems that have established under particular pH ranges. Where significant increases or decreases (for instance 0.2 pH units or more) are predicted, there is a likelihood that native ecosystems will be adversely affected. Again, the most pronounced increases are evident in the southern region, particularly in the alpine regions where increases of more than 0.3 pH units are predicted.

Resources Commission by NSW Department of Planning, Industry and Environment and University of Sydney.

117 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program, Final report v1.1* for NSW Natural Resources Commission by NSW Department of Planning, Industry and Environment and University of Sydney.

118 *Ibid.*

Water quality, flows and waterway health

Forecasts of larger and more intense wildfires are concerning given that wildfires can trigger widespread increases in erosion rates with major implications for water quality and waterway health.[119] Typically, the infiltration capacity of forest soil is reduced after a fire and sediment transport into streams increases. For example, after high severity wildfire sediment transport into waterways is often 1-2 orders of magnitude higher than background rates.[120]

Large scale disturbances such as the 2019-20 fires can also fundamentally change forest hydrology and increase the recovery time for waterways, particularly if regeneration is suppressed by multiple fires.[121] Recent research[122] assessing the impacts of the 2019-20 bushfires on Coastal IFOA outcomes suggested it was likely that the fires increased the potential for significant soil erosion during the rainfall events that followed, particularly on ridges and upper slopes. Following the 2019-20 wildfires, modelled soil erosion risk increased by 143 percent in state forests and 113 percent in national parks, with the highest average post-fire erosion rates predicted in the NSW North Coast and South East Corner bioregions.[123]

Similarly, the projected rise in intense rainfall events also has the potential to affect water quality in forested catchments, with increases in erosion rates and sediment delivery expected with the predicted increased intensity and duration of rainfall events. Reducing sources of erosion and sedimentation arising from forestry activities – particularly by improving the forest road network and drainage crossings – will become increasingly important in this context.
In addition, more frequent cycles of drought and recovery are also likely to further exacerbate recent trends around declining stream flow quantity in forest catchments (**Section 1.1**), with the potential for associated impacts on water quality.

1.5 South coast and alpine regions are most at risk

1.5.1 High risk regions following the 2019-20 wildfires

The South Coast

South coast forests support a range of biodiversity, cultural, social and economic values. For example, this region includes key habitat areas such as the Murrah Koala Flora Reserves, which provide habitat for the last significant koala population on the NSW south coast, as well as other threatened species such as the long-nosed potoroo, yellow-bellied glider and powerful owl.[4] Over 40 percent of the South East Corner bioregion is dedicated to the reserve system.

119 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

120 Alluvium (2020). *Review of the current state of knowledge for the monitoring of forestry impacts on waterway health in NSW coastal forests*. Report for the Natural Resources Commission.

121 Guo, D., Hou, X., Saft, M., Webb, J.A., Western, A.W. (2010) *Report for NRC Forest Baseline & Trend Indicators - Project 3 Task 2 - Long-term trends of Water Quality and Quantity in NSW RFA forests*. University of Melbourne.
Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

122 Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub, commissioned by the NSW Forest Monitoring Steering Committee, Sydney, NSW

123 NSW and Department of Planning, Industry and Environment (2020). *NSW Fire and the Environment 2019–20 Summary Biodiversity and landscape data and analyses to understand the effects of the fire events*. Available at: NSW Fire and the Environment 2019-20: Summary

As described throughout **Sections 1.2** and **0**, the 2019-20 wildfires were more intense in southern coastal NSW than in northern coastal NSW, both in terms of extent and intensity. Many state forests and national parks were affected, including the north-western edges of the Murrah Koala Reserves. There was a large shift into higher risk categories for vegetation on the south coast based on fire frequency thresholds. The fires also impacted the timber industry, with substantial declines in wood supply and sustainable yield forecasts. The south coast was also shown to have experienced the largest declines in catchment flows over the last 30 years, and to be under pressure from invasive species such as cats and foxes.

The south coast forests – along with the species, communities and industries that depend on them – are therefore considered particularly vulnerable to subsequent disturbances and impacts in the short-term during the post-fire recovery period.

Australian Alps

The Australian Alps bioregion (the Alps) in NSW has been highlighted as an area of concern based on an analysis[124] of post-fire vegetation recovery, as this area:

- had the lowest proportion of post-fire recovery in this study
- is generally dominated by slow-growing, fire-sensitive species and is likely to be sensitive to environmental change
- has had recent increases in fire frequency that exceed the historical average
- includes areas with positive flammability feedback dynamics, this is where recently burned forests are more flammable than mature forests.

Much of the Australian Alps is part of the Kosciuszko National Park, dedicated for conservation outcomes and recreation. This is the largest national park in NSW and contains unique glacial landscapes and unusual assemblages of plants and animals that are not found elsewhere.[125] A recent survey confirmed that there is a koala population in the south-eastern region of Kosciuszko National Park, as well as other threatened species including the southern greater glider and the yellow-bellied glider.[126]

The 2019-20 fires affected a third of the national park (around 231,000 hectares or 34 percent).[127] A study focusing on adjacent alpine areas in Victoria, specifically areas dominated by *Eucalyptus pauciflora* subsp. *niphophila* (Snow Gum, Myrtaceae), showed that woodland structure in areas dominated by this species has been altered due to frequent fire.[128] Areas subject to fire twice within a decade were shown to have no saplings above the treeline, despite saplings being common pre-fire. Fire frequency also affected the stand structure of subalpine woodlands, highlighting the risk to recruitment in sensitive alpine areas subject to frequent fires.

Alongside the fire impacts, the Alps region is under pressure from threats such as pests, weeds and dieback. For example, a study in Kosciuszko National Park showed that grazing pressure from pest animals – predominantly from feral horses, but also from deer – has increased in recent decades, with significant environmental impacts.[129] Impacts associated with feral horse populations include changing vegetation structure, damage to stream banks and reduction in

124 Gibson, R.K. and Hislop, S. (2022), Signs of resilience in resprouting Eucalyptus forests, but areas of concern: 1 year of post-fire recovery from Australia's Black Summer of 2019–2020, *International Journal of Wildland Fire,* 31, 545-557.

125 Department of Planning, Industry and Environment (2006). *Kosciuszko National Park Plan of Management*.

126 Marsh, KJ; Skewes, J; and Lindemayer, D (2022). *Koala surveys in Kosciuszko National Park - Final report*, report by Australian National University for the NSW National Parks and Wildlife Service

127 Department of Planning, Industry and Environment (2020). *Resort Round-up Newsletter Autumn 2020*.

128 Naccarella A, Morgan JW, Cutler SC, Venn SE (2020) Alpine treeline ecotone stasis in the face of recent climate change and disturbance by fire. *PLoS ONE* 15(4): e0231339

129 Ward-Jones, J., Pulsford, I., Thackway, R., Bishwokarma, D. and Freudenberger, D. (2019), Impacts of feral horses and deer on an endangered woodland of Kosciuszko National Park. *Ecol Manag Restor*, 20: 37-46.

water quality.[130] They also threaten native fauna due to changes in vegetation, competition for food resources and destruction of burrows.[131]

Weeds are also an issue, with non-native species being spread across the region by activities like grazing, construction, tourism and recreation (including ski resorts).[132] Weed management is complicated in high conservation value alpine regions as various control options, including the use of specific herbicides, may not be suitable in these areas.[133]

To the south east of the Alps, extensive dieback of the dominant eucalypt species (*Eucalyptus viminalis*, known as the manna gum, white gum or ribbon gum) has also been observed across the Monaro plains, which may have serious ecological implications for that region and surrounding areas, including the Alps.[134] Further, dieback incidents are reportedly spreading to different eucalypt species and new areas, including to the southern areas of Namadgi National Park in the Australian Capital Territory, which adjoins the Alps region to the north-east.[135]

1.5.2 Future pressures and threats due to climate change

Looking further ahead, regions like the Australian Alps and South Coast are also anticipated to be at highest risk from projected changes in climate and fire activity.

Specifically, these regions are expected to experience increases in temperature in both the near- and far-future (**Figure 20**) and decreases in annual rainfall in the near-future (**Figure 21**). Notably, **Figure 21(b)** shows that areas around the Alps are not expected to experience the longer-term increases in annual rainfall forecast across other areas of the state.

The southern alps are also predicted to lose the largest quantity of soil organic carbon under climate change scenarios, while also experiencing the most pronounced increases in soil pH, with predicted increases of more than 0.3 pH units.[136]

A recent paper highlighted three key threats for the Australian Alps due to climate change: reduced snow cover (depth and duration); increased fire frequency and severity; and a shift in vegetation composition from alpine to sub-alpine vegetation communities.[137] In addition, weeds that are currently limited by climatic conditions to sub-alpine environments are expected to expand their distribution under the warmer conditions forecast in climate change projections.[138]

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130 Driscoll, D.A., Worboys, G.L., Allan, H., Banks, S.C., Beeton, N.J., Cherubin, R.C., Doherty, T.S., Finlayson, C.M., Green, K., Hartley, R., Hope, G., Johnson, C.N., Lintermans, M., Mackey, B., Paull, D.J., Pittock, J., Porfirio, L.L., Ritchie, E.G., Sato, C.F., Scheele, B.C., Slattery, D.A., Venn, S., Watson, D., Watson, M. and Williams, R.M. (2019), Impacts of feral horses in the Australian Alps and evidence-based solutions. *Ecol Manag Restor*, 20: 63-72. https://doi.org/10.1111/emr.12357

131 *Ibid.*

132 Frances M. Johnston, Catherine M. Pickering (2001). Alien Plants in the Australian Alps, *Mountain Research and Development*, 21(3), 284-291

133 *Ibid.*

134 Ross C, Brack C. 2015. Eucalyptus viminalis dieback in the Monaro Region, NSW. *Australian Forestry* 78: 243–253. doi:10.1080/00049158.2015.1076754

135 C. Ross & C. Brack (2017) Monaro dieback: simple answers are too simple, *Australian Forestry*, 80:2, 113-114, DOI: 10.1080/00049158.2017.1311762

136 Moyce MC, Gray JM, Wilson BR, Jenkins BR, Young MA, Ugbaje SU, Bishop TFA, Yang X, Henderson LE, Milford HB, Tulau MJ, (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program, Final report v1.1* for NSW Natural Resources Commission by NSW Department of Planning, Industry and Environment & University of Sydney.

137 Hoffmann, A.A., Rymer, P.D., Byrne, M., Ruthrof, K.X., Whinam, J., McGeoch, M., Bergstrom, D.M., Guerin, G.R., Sparrow, B., Joseph, L., Hill, S.J., Andrew, N.R., Camac, J., Bell, N., Riegler, M., Gardner, J.L. and Williams, S.E. (2019), Impacts of recent climate change on terrestrial flora and fauna: Some emerging Australian examples. *Austral Ecology*, 44: 3-27. https://doi.org/10.1111/aec.12674

138 Frances M. Johnston, Catherine M. Pickering (2001). Alien Plants in the Australian Alps, *Mountain Research and Development*, 21(3), 284-291

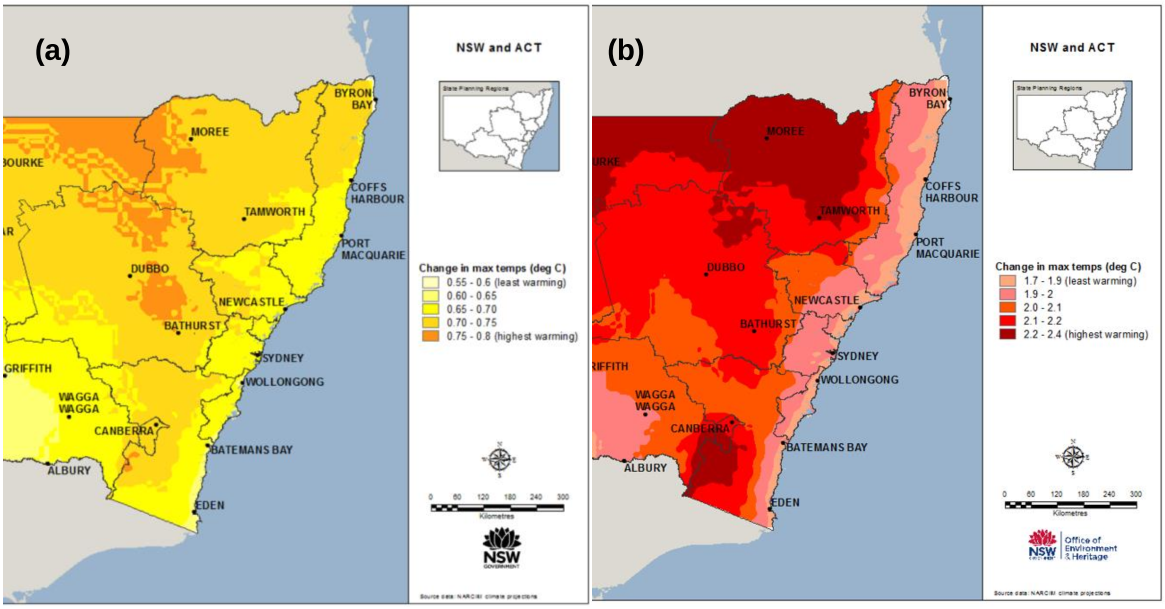

Figure 20: Projected changes in mean daily annual maximum temperatures for (a) near-future change period (1990-2009 to 2020-39) and (b) far-future change period (1990-2009 to 2060-79)[139]

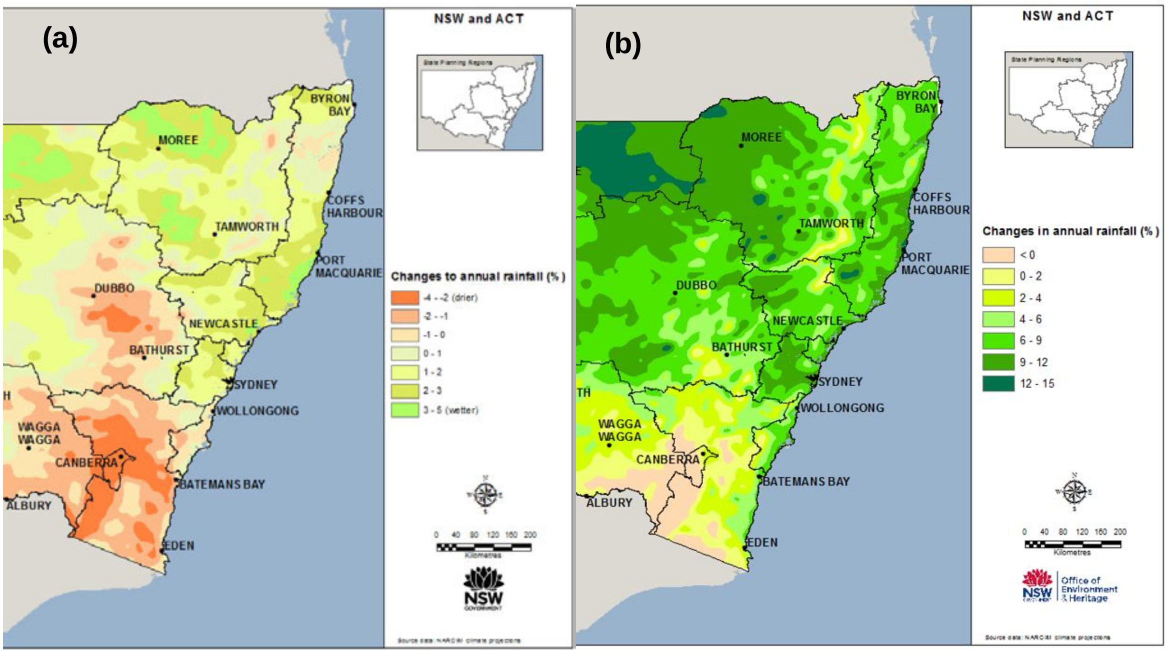

Figure 21: Projected changes in mean annual precipitation for (a) near-future change period (1990-2009 to 2020-39) and (b) far-future change period (1990-2009 to 2060-79)[140]

139 AdaptNSW NSW Climate Change Snapshot: https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/Climate-projections-for-your-region/NSW-Climate-Change-Downloads

140 *Ibid.*

2 Managing the natural capital within NSW forests

The findings presented in the first section of this report provide insights into the status and trajectory of NSW's forests, and the future challenges forests and forest managers are facing. In this section, this evidence is used to inform a discussion about what can be done to protect, maintain and enhance future forest values.

2.1 Action is needed to prevent loss of future forest values

In future forest scenarios developed under the FMIP, a panel of leading experts in forestry, resilience and future thinking concluded that a business-as-usual approach would result in reduced and declining forest values.

Without intervention, existing pressures – such as land-use change, habitat fragmentation and degradation, and invasive species – will combine with new threats from climate change and repeated shocks from disturbances like droughts, fires and floods. The result will be ongoing declines in the resilience, health and productivity of NSW forests, particularly in higher risk areas such as alpine regions and the south coast of NSW. It is therefore likely that the values and services currently supported by NSW forests in high-risk regions may decrease in the future.

There is potential for more positive future pathways in which the social and economic values of forests and emerging risks from climate change are recognised and actively managed across all tenures. Recent natural disasters have highlighted the central role of the environment in human well-being, and there is increasing community demand for leadership and investment in environmental management to protect our natural resources and the associated benefits and services they provide.

A central theme of the recent *2021 Australian State of the Environment report*[141] is the importance of the environment to human wellbeing. It sets out the ongoing challenges and threats facing our environment and the concerning declining trends observed for many environmental values. The report calls for a more strategic focus on planning for a sustainable future, new, reliable sources of funding and integrated policies and management actions to address drivers of environmental change.

The NSW Government is increasingly recognising the value of natural capital and is currently developing a *NSW Natural Capital Statement of Intent*, which will guide and inform government decision-making around environmental assets and services.[142] This approach highlights the interlinkages between the economy and environmental assets and services, and the importance of natural capital in shifting towards a sustainable, low-carbon emission future that strikes a balance between maintaining and enhancing natural capital and promoting economic growth.

The *NSW Climate Change Adaptation Strategy* also sets out range of priorities to prepare and respond to climate change. The Government has committed over $93 million over the next 8 years to deliver the strategy, including initiatives such as scenario analysis and risks assessment. Information generated under the FMIP – such as scenario analysis, fauna models and baseline data – are critical inputs to inform strategic actions.
Given this policy context and likely future challenges, the time is right for renewed and sharper focus on forests and the essential values and services they provide, supported into the future by strategic, coordinated management and adequate investment through long-term funding. In the following sections we set out initiatives that will address these challenges.

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141 Commonwealth of Australia (2021) *Australia State of the Environment 2021*, Commonwealth of Australia, Canberra, ACT

142 NSW Government (2022). *Consultation Draft NSW Natural Capital Statement of Intent*.

2.2 Understanding and managing carbon balances

Direct coordinated action is needed to address the growing climate risk, including actions to monitor and reduce carbon emissions. In relation to NSW forests, relevant NSW Government plans and objectives include:

- NSW Government's overarching objective to achieve net zero emissions by 2050, supported by the NSW Climate Change Adaptation Strategy[143] and the Net Zero Plan Stage 1: 2020-2030[144]
- NSW National Parks and Wildlife Service's **net zero to carbon positive by 2028** action plan, whereby carbon sequestration in national parks eventually exceeds emissions associated with park management activities, including the following targets:
  - **2025 target**: reduce carbon emissions by 55 percent
  - **2028 target**: reach net zero and become carbon positive[145]
- NSW Environment Protection Authority's draft **climate change policy**[146] and **action plan**[147] to meet their statutory objectives and obligations and support NSW Government's broader objectives, including committing to being **carbon-neutral by 2030**
- Forestry Corporation of NSW must meet the Australian Standard for Sustainable Forest Management to retain their sustainable forest management certification, which includes a criterion around **maintaining forests' contribution to the carbon cycle**.

NSW forests are a significant carbon resource contributing to the global carbon cycle, with the potential to either deliver beneficial carbon capture or contribute to carbon emissions. The findings presented within this report suggests that, without a major intervention, NSW forests may shift from a carbon storage to net carbon emitter in the coming decades, undermining key Government carbon emission commitments.

However, a key goal of sustainable forest management is maintaining or enhancing forest carbon stocks. With appropriate management and interventions, NSW forests can contribute to mitigating carbon emissions through carbon capture and storage. Monitoring, modelling and research is needed to determine which approaches and interventions – such as prescribed burning, mechanical thinning and harvesting, assisted regeneration, and/or tree retention/avoided losses – will maximise carbon storage while also maintaining productivity and addressing risks from increased fire activity.[148]

As highlighted previously in this report, there are underlying assumptions within current carbon accounting around the capacity of forest recovery to effectively offset carbon emissions associated with forestry activities and other disturbances such as fire and drought. These emissions are currently considered to be temporary and are not included in long-term net carbon emission totals. However, there is a significant risk that climate change and changing disturbance regimes may undermine the ability of affected areas to recover, leading to a

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143 NSW Government (2022) *NSW Climate Change Adaptation Strategy*, NSW Government.

144 Department of Planning, Industry and Environment (2020). *Net Zero Plan Stage 1: 2020–2030*, Environment, Energy and Science (in Department of Planning, Industry and Science) on behalf of the NSW Government

145 NSW Department of Planning, Industry and Environment (2021). *NSW National Parks and Wildlife Service - Carbon Positive by 2028*, Environment, Energy and Science, Department of Planning, Industry and Environment

146 State of New South Wales and the NSW Environment Protection Authority (2022), *Environment Protection Authority Climate Change Policy – Draft for consultation*. NSW Environment Protection Authority, Parramatta NSW.

147 State of New South Wales and the NSW Environment Protection Authority (2022). *Environment Protection Authority Climate Change Action Plan 2022–25 – Draft for consultation*. NSW Environment Protection Authority, Parramatta NSW.

148 Bowman, D.M., Williamson, G.J., Price, O.F., Ndalila, M.N. and Bradstock, R.A., 2021. Australian forests, megafires and the risk of dwindling carbon stocks. *Plant, Cell & Environment*, *44*(2), pp.347-355.

commensurate increase in carbon emissions and jeopardising Government's ability to meet its stated emissions targets. Accordingly, forest recovery needs to be monitored to determine whether the rate of recovery (and thus carbon capture) is meeting expectations, with the capacity to trigger active interventions to improve regeneration outcomes as needed.

At the state scale, ongoing monitoring and assessment of trends in forest carbon are needed to determine whether the range of chosen management approaches being applied across NSW forests are achieving the desired carbon storage outcomes, and whether overall emissions targets are being met. The FMIP delivered a comprehensive spatial and temporal analysis of the carbon balance in NSW forests from 1990 to 2020.[149] This research advanced the understanding of forest carbon balances and trends across NSW over the past 30 years, laying a foundation for ongoing assessment and accountability around forest carbon and carbon emissions in NSW.

In addition, investment in soil monitoring needs to increase to support accurate carbon accounts and management. For example, in the last decade less than 50 soil carbon measurements have been collected by government across NSW Regional Forest Agreement regions.[150]

2.2.1 Strengthening regulation with the best available science

To support Government policy objectives and statutory obligations for climate change, the Government should incorporate the latest climate science and forest data for upcoming regulatory reviews such as for the Coastal Integrated Forestry Operations Approval (CIFOA) and Land Management Codes – Native Vegetation.

The recently approved PNF Codes of Practice includes a new mechanism to adaptively respond to impacts to unforeseen events, recognising the increasing risk of wildfires, droughts and dieback under predicted changes in climate.[151] There is no such 'force majeure' mechanism in the Coastal IFOA for instance.

Similarly, the revised bilateral RFA agreements recognise 'climate change is driving more extreme weather events' that will impact NSW forests. Both governments have committed new information, including climate change risks and adaptation responses will continue to support RFA implementation. For example, NPWS must identify and integrate relevant climate risks and adaptation responses into the monitoring, evaluation and reporting requirements in Regional ESFM Plans and plans of management under the NSW *National Parks and Wildlife Act 1974*.[152]

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149 Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, Mullion Group.

150 Moyce, M.C.; Gray, J.M.; Wilson, B.R.; Jenkins, B.R.; Young, M.A.; Ugbaje, S.U.; Bishop, T.F.A.; Yang, X.; Henderson, L.E.; Milford, H.B.; Tulau, M.J. (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry and Environment and University of Sydney.

151 See for example, Private Native Forestry – Code of Practice for Northern NSW. Available at https://www.lls.nsw.gov.au/__data/assets/pdf_file/0019/1401661/PNF-Code-Northern-NSW.pdf

152 Cl 48(i) DEED OF VARIATION IN RELATION TO THE REGIONAL FOREST AGREEMENT FOR THE NORTH EAST REGION – Commonwealth of Australia ,and The State of New South Wales

2.3 Addressing threats, increasing resilience and managing risks

Forest owners and managers have a chance now to wisely and proactively invest in improving the health and resilience of forest ecosystems, and addressing anticipated future threats and risks, to avoid major shocks and maintain forest values into the future.

Government should adopt a future-focused approach that draws and expands on the future forest scenarios work initiated under the FMIP.[153] Eight exploratory scenarios have been identified representing different plausible futures for NSW forests to 2050, ranging from optimistic to pessimistic. These scenarios have been developed by experts in forest science, forestry and resilience and future thinking with input from all NSW Government agencies responsible for managing or monitoring NSW forests across all tenures. This work brings forest planning and management in line with best practice approaches used in infrastructure and transport planning.

The future forest scenarios are designed to prompt further exploration of the implications of alternative policy and forest management decisions. These decisions should also be informed by a risk assessment process to identify and target at-risk regions, forest ecosystems, species and/or production systems for proactive management. Priority areas could include areas that are likely to be subject to increased natural disturbances due to climate change, or ecosystems and species that are on a declining trajectory due to ongoing pressures and threats. Evidence such as the FMIP's baseline, status and trend information as informed by future monitoring, climate change scenarios and forest modelling should inform the risk assessment.

Strategic interventions and actions to mitigate priority risks can then be identified, including:

- managing immediate, ongoing threats to forest values such as pests, weeds and clearing
- accelerating or ensuring achievement of forest management outcomes, such as post-fire recovery and regeneration
- managing risks associated with changing climate and increased fire, drought and intense rainfall events.

These intervention strategies, including their intent and potential actions, are outlined further in **Table 2**. However, a strategy outlining the best course of action needs to be carefully assessed and debated based on the best science and dialogue with the community and industry. Success will rely on mutual understanding and broad support for proposed actions. Importantly, any actions need to be supported by monitoring and assess the success or otherwise of the interventions.

Table 2: strategies for interventions in priority areas

Strategy	Intent	Potential actions
Managing immediate, ongoing threats to forest values	Improving the management of existing threats such as habitat loss and degradation and invasive species to increase the health and resilience of forest ecosystems so these areas are better able to endure or adapt to increasing threats and pressures in future	▪ Reducing loss of forest extent due to land clearing ▪ Addressing total grazing pressure in forests, and removing grazing in high-risk areas ▪ Investing in pest and weed control, prioritising horse, fox, feral cat and deer control

153 Cork, S., Ferrier, S., Kanowski, P., & Lade, S. (2022) *NSW Future Forest Scenarios report*, Australian National University.

Strategy	Intent	Potential actions
Active management to accelerate or ensure the achievement of forest management outcomes	Applying targeted and active management interventions to achieve outcomes with a greater degree of control and certainty than naturally occurring processes or passive approaches	▪ Accelerating the provision of essential habitat for fauna with artificial tree hollows[154] that can require 100 years or more to naturally develop ▪ Native forest reforestation and assisted natural regeneration for production and biodiversity outcomes s ▪ Adopting Aboriginal land management practices such as cultural burns to improve forest and soil health
Managing risks associated with changing climate and increased fire, drought and intense rainfall events	Managing emerging and future risks expected as a result of climate change, including heightened fire, drought and flood risks.	▪ Revised fire hazard reduction activities and investment in new rapid response fire suppression technologies ▪ Improving forest road networks to reduce sedimentation in extreme rainfall events ▪ Investing in protection of species at high risk from climate change, including potential assisted migration of species

The Commission notes recent significant issues-based investments towards priority species such as koalas. While these investments have the potential to enhance outcomes for other species, there are likely opportunity costs for other species such as hollow-dependent birds and mammals. In addition, it is likely that increased investment is needed to address broader issues and risks, such as widespread pests and weeds, or sedimentation from the forest road network.

The Commission also notes the NSW Government is investing to improve NSW fire management in response the 2020 independent bushfire inquiry. While the NSW Government periodically reports on progress, an independent assessment on the impact of new fire management technologies on fire frequency and severity and the flow-on effects for forest values and services may be warranted in the future.

When identifying potential management options, decision makers should consider a wide range of approaches and knowledge sources. In particular, identifying opportunities to better involve and learn from Aboriginal peoples, including using Aboriginal land management practices such as cultural burning to improve forest ecosystem health where appropriate (see **Section 0**).

Ideally, forest values should be enhanced across all tenures, including within the reserve system (such as national parks) as well as on multi-use forest tenures (such as state forests) and on private land. As such, any actions and interventions should therefore be strategic, coordinated and applied across all tenures as needed.

154 For example, approaches see Biodiversity Conservation Trust Guideline for Artificial Hollows for Private Land Conservation Agreements (2020)

2.4 Securing values through dedicated funding

The 2019/20 wildfires were unprecedent in their size and severity. The fires were closely followed by floods in 2021 and 2022 directly impacting the health of NSW forests and the values they support for the community and biodiversity.

Governments funded programs in direct response to support community recovery and address immediate impacts on NSW forests – for example, relief programs for wildlife rehabilitators[155] and habitat and species.[156] Funding has shifted to support medium to longer term activities for landscape rehabilitation.[157]

The community has welcomed these initiatives. However, the continued demand for funding is likely given the growing consensus that similar scale events will become increasingly frequent in the future. Reactive, one-off funding decisions to address such events may lead to sub-optimal outcomes, or the permanent loss of key natural and economic assets at worst.

Along with the opportunity to establish a strategic outlook and action plan for NSW forests **(Section 2.3)**, governments also have the opportunity to arrange for a dedicated fund to implement the strategy and respond to significant events. Without additional investment at a forest ecosystem scale there is a real risk that NSW will not be able to secure the asset value and services that NSW forests can provide into the future.

The Commission recognises the competing demands on government budgets particular post-COVID and recent natural disasters. It may be prudent for the government and agencies to consider alternative funding sources that can spread the costs required to secure outcomes from NSW forests between state government and the major commercial and community beneficiaries. For example, the Government could consider recycling land, building and heritage assets, and introducing new levies, micro levies or similar taxes. There also may be more opportunities for greater efficiencies with for instance more effective use of competitive tendering to deliver management activities at a larger, cross-tenure scale.

2.5 Strengthening Aboriginal decision making and management

Recent Aboriginal-led case studies exploring cultural values assessments in NSW forests highlighted that there are significant knowledge gaps around Aboriginal cultural values, particularly where Aboriginal people lack access to, or involvement in, land and its management. There is an opportunity and strong desire from case study participants to build on the outcomes achieved and strengthen the participation of Aboriginal peoples in forest management and decision making.

The case studies also demonstrated the opportunities offered by Aboriginal-owned and managed tenures, specifically Indigenous Protected Areas. These areas benefit from resourcing for Ranger groups, the ability to lead planning and management from a Country and landscape perspective, locally based training and employment, opportunities for youth education and involvement, and access to and sharing of knowledge from Elders and knowledge holders.

There have been several recent NSW Government initiatives that offer opportunities to expand Aboriginal peoples' involvement and leadership in land management – this is in line with the Closing the Gap targets for increasing legal rights and interests in land and water. A key example is the proposal to expand and develop the model for Aboriginal joint management of

155 https://www.environment.nsw.gov.au/topics/animals-and-plants/native-animals/helping-wildlife-in-emergencies/bushfire-relief-for-wildlife-rehabilitators
156 https://www.dcceew.gov.au/environment/biodiversity/bushfire-recovery/funding-support
157 https://www.dcceew.gov.au/environment/biodiversity/bushfire-recovery/activities-and-outcomes/phase-2#approved-projects

the NSW national park estate, in consultation with Aboriginal people and other national park stakeholders. This offers an opportunity to increase Aboriginal involvement in land management and custodianship, including the ability to trial new joint management models and approaches.

The expansion of Aboriginal land management, cultural fire, and ranger programs has also been explored by other agencies including Local Land Services and the Forestry Corporation of NSW. These programs offer a way of improving environmental, social and economic outcomes, including by enhancing Aboriginal peoples' connection to Country, sharing knowledge of land and water management, and providing meaningful training and career pathways.

A key recommendation emerging from the Aboriginal-led case studies is support for 'whole of Country' planning processes. These processes help Aboriginal groups to proactively develop and share their aspirations and desired outcomes for Country with other land managers and highlight opportunities for partnership, training, investment and leadership.

The Commission and Local Land Services have advanced an early proposal to pilot a Whole-of-Country plan in collaboration with the Banbai Rangers and Guyra and Tamworth Local Aboriginal Land Councils, and NSW Department of Aboriginal Affairs. The pilot aligns with the NSW Government's Closing the Gap land and water targets and has received support and endorsement from key partner agencies including Aboriginal Affairs NSW, NSW Aboriginal Land Council, Department of Planning and Environment, NSW National Parks and Wildlife Service and Forestry Corporation of NSW.

2.6 Informing decision making and providing assurance

To provide relevant evidence and assurance, there is a clear need for increased, long-term investment in monitoring, evaluation and research for forest management, as well as ongoing funding for existing monitoring programs for the Coastal IFOA, Private Native Forestry Codes and Regional Forest Agreements.

As highlighted previously, forest values are already under pressure, with threats expected to increase further over time based on climate change projections. As the climate changes, we will need to identify and apply interventions to increase forest resilience and maintain carbon balances, many of which may be new approaches that involve a shift away from some long-accepted forest management practices. In this context, it is essential that we make informed decisions about how these areas are managed to try to maintain the values of these forests, based on best available knowledge and evidence.

Arguably, we are entering a state of heightened uncertainty and that existing knowledge is not necessarily going to be a good predictor of the future. Decision makers will increasingly need to draw on new research and monitoring, scenarios, data and modelling approaches to provide assurance of current management and predict what future forests will look like under various climate change and management scenarios. This will help identify key risks, priority areas for investment and appropriate land management actions and policy. Government will also need evidence to be able to predict and measure the effectiveness of various intervention options in different contexts.

The Commission notes that funding for cross-tenure forest monitoring overseen by the NSW Forest Monitoring Steering Committee ceased in Financial Year 2022, and that going forward forest monitoring on the reserve system will be carried out separately by NPWS. However, the Commission still considers cross-tenure monitoring – based on consistent methods and datasets - is critical to reliably evaluate management effectiveness and performance.

The Forest Monitoring Steering Committee will continue to oversee existing legal mandates to monitor the effectiveness of the Coastal IFOA and Private Native Forestry Codes. The

Environment Protection Authority's draft *Climate Change Action Plan 2022–25*[158] highlights the role of the FMIP in ensuring climate risks in native forestry are identified and consequences are appropriately managed under the IFOAs and Private Native Forestry codes. This aligns with Priority 1 under the broader *NSW Climate Change Adaptation Strategy*[159] to develop robust and trusted metrics and information on climate change risk.

The Local Land Services have recently committed $1.5 million over two years to commence monitoring, assessments and model improvements under the new Private Native Forestry Codes. A similar amount and long-term commitment to meet Coastal IFOA monitoring obligations is also needed when funding ceases in Financial Year 2023.

The current mandate to oversee monitoring on production forests could be further extended to other NSW IFOAs, including the River Red Gum IFOA. Further, the mandate to coordinate monitoring for Regional Forest Agreements should be formally reinstated in-line with bilateral agreements between the NSW and Australian Governments. This will ensure the NSW Government has the necessary evidence to support its commitments under the *NSW Forestry Industry Roadmap* and to continue to meet its broader national and international obligations for ecological sustainable forest management.

[158] State of New South Wales and the NSW Environment Protection Authority (2022). *Environment Protection Authority Climate Change Action Plan 2022–25 – Draft for consultation*. NSW Environment Protection Authority, Parramatta NSW.

[159] NSW Government (2022) *NSW Climate Change Adaptation Strategy*, NSW Government.

Attachment A – Forest Monitoring and Improvement Program overview

The FMIP delivers monitoring, evaluation, and reporting for NSW forests to improve the strategic and adaptive management of these forests over time. The FMIP was developed by the NSW Forest Monitoring Steering Committee, which is independently chaired by the Natural Resources Commission.

The NSW Forest Steering Committee is also overseeing the Coastal Integrated Forestry Operations Approval (Coastal IFOA) Monitoring Program and the Private Native Forestry Codes of Practice Monitoring Program. These programs evaluate whether the forestry activities under each instrument are achieving objectives and outcomes.

Although the FMIP is a state-wide, cross-tenure program, the various monitoring and research programs focus on different spatial scales, most often targeting the area covered by the Regional Forest Agreements and Coastal IFOA (**Figure A**).

Forest monitoring programs and research projects

The FMIP is generating data and applying a range of analytical approaches to build a stronger evidence base to inform forest management. Over the last three years, the FMIP has invested over $6 million in research projects to define baselines and identify past trends and drivers of change for NSW forests. As well as providing insights into the past trajectories and current status of NSW forests, these projects provide a foundation and tools for evaluating future scenarios, risks and management options.

Research projects have collected baseline, driver and trend evidence for the following themes:

- forest ecosystem health
- biological diversity
- soil and water resources
- productive capacity and sustainability
- contribution to global carbon cycles.

In addition, the FMIP has invested in a range of other projects focused on areas such as Aboriginal values and renewal post-fire, koala and habitat response post-fire, quantifying forest-dependent jobs, promoting citizen science, and developing future scenarios for NSW forests.

Up to 40 partners have been involved in these projects, including leading universities, Aboriginal organisations, consultancies and NSW agencies. A range of scientific approaches have been used including retrospective analysis to develop baselines, field monitoring and remote sensing, and various modelling approaches.

In addition, there have also been projects commissioned under the Coastal IFOA Monitoring Program that have delivered findings that can help inform broader forest management under the FMIP. Priority monitoring and actions will also soon commence for the Private Native Forestry Monitoring Program.

Relevant FMIP and Coastal IFOA Monitoring Program monitoring and research projects are shown in **Table A**, and the key findings from each are summarised in **Table B**. More information about the completed and ongoing research projects can be found on the Commission's website.

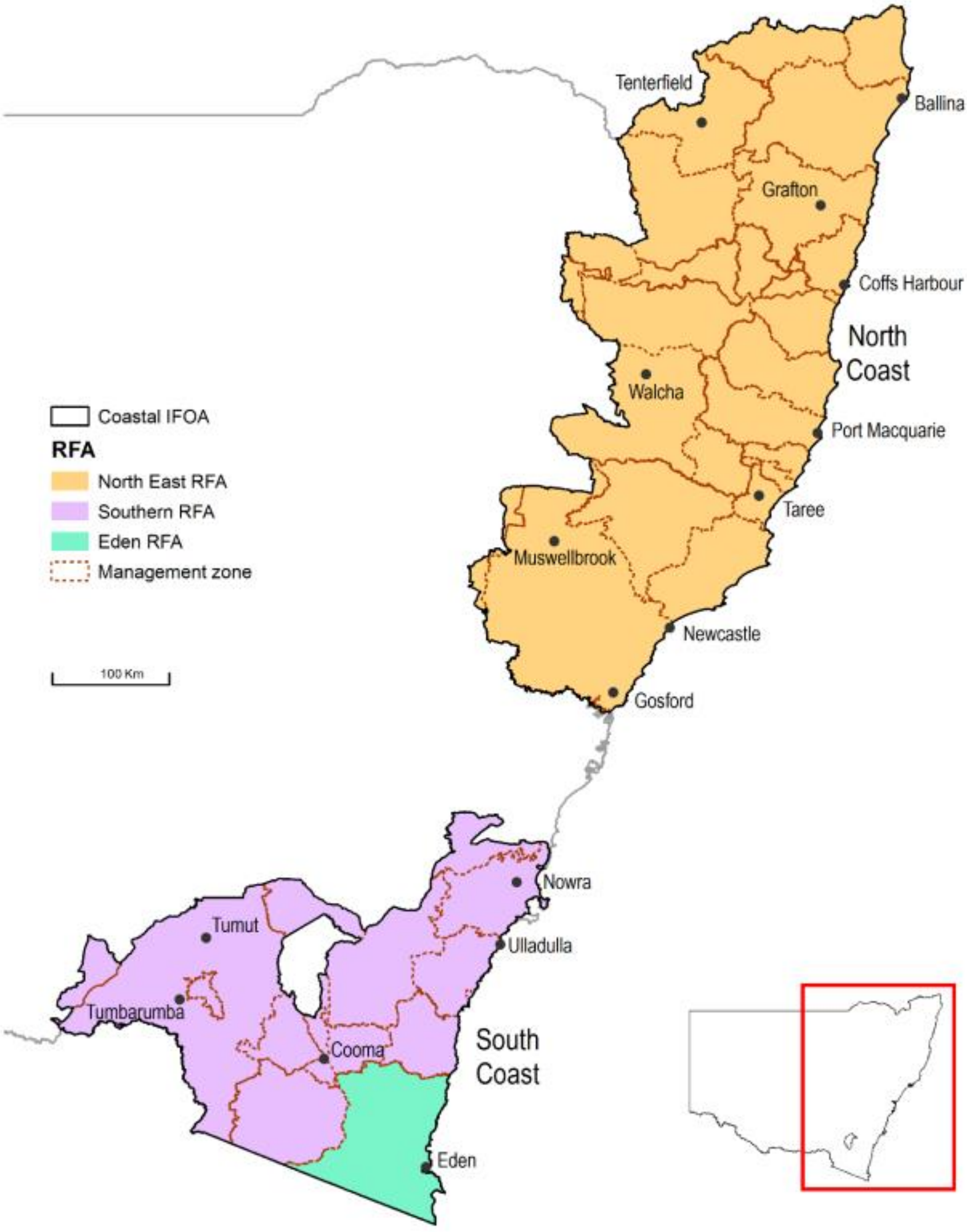

Figure A: Map showing the area of NSW covered under the Regional Forest Agreements (RFA) and Coastal IFOA

Table A: FMIP and Coastal IFOA Monitoring Program monitoring and research projects

Theme	Project title	Research team(s)	Description	Reference
Forest ecosystem health	FMIP Project FE1: Baselines, drivers and trends for forest extent, condition and health	Spatial Vision, RMIT University and PF Olsen	Sourcing historical and current datasets to establish and interpret drivers of trends in forest extent, condition and health, with an initial focus on NSW Regional Forest Agreement regions. Determining forest extent using the Landsat 25 metre grid resolution to provide annual temporal coverage from 1988 to 2019 for eastern NSW.	Spatial Vision (2022) Forest monitoring – Extent Methodology Associated dataset Spatial Vision (2022) Forest monitoring – Condition methodology Associated dataset Spatial Vision (2022) Forest monitoring – Forest loss and recovery Associated dataset
Biological diversity	FMIP Project BD1: Baselines, drivers and trends for species occupancy and distribution	University of New England, Macquarie University, NSW DPI – Forest Science, and NSW DPE	Establishing baselines in species occupancy using historical data and indicators and modelling from the NSW Biodiversity Indicators Program. Species occupancy modelling and environmental niche modelling analyses for priority fauna species. Flora community analyses for each Regional Forest Agreement region and preparation of a list of priority plant species. Analysing species trends since the 1990s where sufficient data exists.	Kavanagh,R., Law, B., Drielsma, M., Gonsalves, L., Beaumont, L., Jenkins, R., Wilson, P.D., Binns, D., Thinley, P., Bulovic, N., Lemckert, F., Brassil, T., & Reid, N. (2022), *NSW Forest Monitoring and Improvement Program Project 2: Baselines, drivers and trends for species occupancy and distribution – Final Report*.
	Project BD4: Koala and habitat response post-wildfires	Australian National University, University of Western Sydney and NSW DPI – Forest Science	Building on the Commission's koala research program, researchers from the Australian National University, University of Western Sydney and the NSW Department of Primary Industries will investigate how koalas, and their habitat – for example, occupancy and nutritional content of regeneration trees - respond in a post-fire landscape on the NSW north coast.	Natural Resources Commission (2022), *Summary paper - koala and habitat response after the 2019-20 wildfires*,

Theme	Project title	Research team(s)	Description	Reference
Soil and Water resources	FMIP Project SW1: Baselines, drivers and trends for forest water catchments	University of Melbourne	Delivering baselines, drivers and trends for water quality and quantity in the NSW Regional Forest Agreement areas.	Guo, D., Hou, X., Saft, M., Webb, J.A., Western, A.W. (2010) *Report for NRC Forest Baseline & Trend Indicators - Project 3 Task 2 - Long-term trends of Water Quality and Quantity in NSW RFA forests*, University of Melbourne.
	FMIP Project SW2: Baselines, trends and drivers for soil stability and health in forest catchments	NSW DPE, the University of Sydney and the University of New England	Delivering baselines, drivers and trends for soil stability and health in forest catchments across the NSW Regional Forest Agreement areas.	Moyce, M.C.; Gray, J.M.; Wilson, B.R.; Jenkins, B.R.; Young, M.A.; Ugbaje, S.U.; Bishop, T.F.A.; Yang, X.; Henderson, L.E.; Milford, H.B.; Tulau, M.J. (2021). *Determining baselines, drivers and trends of soil health and stability in New South Wales forests: NSW Forest Monitoring & Improvement Program*, NSW Department of Planning, Industry and Environment and University of Sydney.
	FMIP Project SW3: Evaluating forest road network to protect forest waterways	Alluvium and the NSW Soil Conservation Service		Alluvium (2022). *Evaluating forest road networks to protect water quality in NSW: final report*, Alluvium, unpublished report.
Productive capacity and sustainability	FMIP Project PC1: Baselines and trends in wood supply	Indufor	Establishing historical baselines and trends in wood supply from NSW coastal native state forests, specifically historic actual wood supply and drivers of change in wood supply in the period 2003-2019.	Indufor (2022). *Coastal Integrated Forestry Operations Approval Monitoring Program - Monitoring wood supply baseline and trends*. Report prepared for the NSW Forest Monitoring and Improvement Program, Natural Resources Commission, Sydney N.S.W.
Contribution to global carbon cycles	FMIP Project CC1: Carbon balance of NSW forests	Mullion Group, NSW DPI and the CSIRO	Quantifying the carbon balance of NSW forests and how this may change under different policy, management and climate scenarios.	Roberts, G., Waterworth, R., de Ligt, R., McKenzie-McHarg, H., Francis, M., Roxburgh, S., Paul, K., Ximenes, F., (2022) *Carbon Balance of NSW Forests – Methodology and Baseline Report*, Mullion Group.

Theme	Project title	Research team(s)	Description	Reference
Aboriginal values and management	FMIP Project AV2: Aboriginal values and renewal post-fire - Case studies	Firesticks, Coffs Harbour, Tamworth and Brungle-Tumut Local Aboriginal Land Councils	The Coffs Harbour, Tamworth and Brungle-Tumut Local Aboriginal Land Councils will lead on-ground values and renewal assessment in their respective regions. The case studies will be guided by local steering groups and undertake assessments of diverse Aboriginal values before and after the 2019-20 wildfires. Actions will be identified to support cultural restoration and renewal in the forests. These case studies are part of a broader approach to develop a model to assess Aboriginal values across forest tenures, through Aboriginal-led, country-based assessments, monitoring, and research.	Firesticks Alliance Indigenous Corporation (2022), *Aboriginal Cultural values and renewal in NSW forests post-wildfires - Synthesis report*, Firesticks Alliance Indigenous Corporation. Banbai Rangers and McKemey, M. (2021) 'Aboriginal cultural values and renewal assessment in NSW forests post-wildfires - Banbai case study report'. Report prepared for the NSW Forest Monitoring and Improvement Program, Natural Resources Commission, Sydney N.S.W. Coffs Harbour and District LALC with Gumbaynggirr Elders and Knowledge Holders (2022) Aboriginal cultural values and renewal assessment in NSW forests post-wildfires Gumbaynggirr Lands. Report prepared for the NSW Forest Monitoring and Improvement Program, Natural Resources Commission, Sydney N.S.W. Herrington, S & Byron, N. (2022) Aboriginal Cultural values and renewal assessments in NSW forests post – wildfires Case Study Report. Brungle-Tumut LALC. Report prepared for the NSW Forest Monitoring and Improvement Program, Natural Resources Commission, Sydney N.S.W
Future scenarios	FMIP Project: NSW Future Forest Scenarios Project	Australian National University, CSIRO	Developing scenarios for the future of NSW forests. These will include alternative futures that emphasise different forest values and community expectations from the short to long-term.	Cork, S., Ferrier, S., Kanowski, P., & Lade, S. (2022) *NSW Future Forest Scenarios report*, Australian National University.

Theme	Project title	Research team(s)	Description	Reference
Other	Coastal IFOA Project: Implications of changing fire intensity and regimes on Coastal IFOA objectives and outcomes	NSW Bushfire Risk Management hub, University of Wollongong	Evaluating: ▪ specific risks to achieving the Coastal IFOA objectives and outcomes as result of the legacy landscape scale impacts of the NSW 2019-20 wildfire season ▪ broad implications of predicted changing fire regimes on the achievement of the Coastal IFOA's objectives and outcomes options to mitigate risks.	Bradstock. R, Bedward, M., & Price, O. (2021). *Risks to the NSW Coastal Integrated Forestry Operations Approvals Posed by the 2019/2020 Fire Season and Beyond*, Centre for Environmental Risk Management of Bushfires, University of Wollongong and the NSW Bushfire Risk Management Research Hub.

Summary of key findings from monitoring and research projects

Table B: Key findings from FMIP and Coastal IFOA Monitoring Program monitoring and research projects

	Status and trend	Outlook
Forest extent and condition *Gradual increase – particularly on private land – followed by reduction due to 2019-20 wildfires* *Robust datasets in place and improving*	▪ Pre-fire, overall forest canopy cover extent had increased between 1995-2020 in coastal NSW by around 5.1 percent, with most increases on private land. ▪ The 2019-20 wildfires caused a significant reduction in forest canopy cover in coastal NSW to below 1995 levels - the fires were more extensive and severe on the South Coast and affected national parks and state forests to a greater extent than private land. ▪ Affected areas are considered particularly vulnerable to impacts from subsequent disturbances in the next 5 to 10 years while burnt forested areas regenerate ▪ Only 10 percent of forested vegetation in the Coastal IFOA area are currently within their recommended fire frequency thresholds, while larger areas – including 60-70 percent of national parks and state forests – are now in classed as 'vulnerable' and 'too frequently burnt' and are at risk of a decline in plant diversity.	▪ Future climates with more prolonged drought, and more frequent and severe heatwaves and bushfires may change the function and structure of many forest types. ▪ Multiple severe fires in quick succession can reduce regenerative capacity of the forest, potentially impacting ecosystem recovery and future timber supply. ▪ Long-term resilience of wildfire refugia may be reduced by more extreme fire weather, with previously sheltered areas potentially affected by more severe or extensive fire.
Forest carbon *Period of stability followed by large release of carbon due to 2019-20 wildfires* *Poor datasets for soil carbon*	▪ Total forest carbon remained relatively stable from 1990 to 2019, varying between 1,438 and 1,559 million tonnes. ▪ There has been a net loss of forest carbon within NSW between 1990 and the end of 2020, estimated at around 164 Mt of carbon (excluding soil) under a 'mid' growth scenario. ▪ The net loss is primarily driven by the 2019-20 fire season, which resulted in significantly larger changes in forest carbon than at any other point in the preceding three decades.	▪ Temporary nature of carbon emission impacts relies on forests' ability to recover and regenerate after disturbance, which may be undermined in the future by more frequent and intense disturbance events.

	Status and trend	Outlook
	▪ It is expected that the 2019-20 emissions due to wildfire will largely be offset by carbon reabsorption during regeneration over the next 10-15 years.	
Biological diversity *Significant habitat impacts from 2019-20 fire, including impacts on koalas* *Analysis significantly improved knowledge base* *Need significant investment in long-term, large scale monitoring*	▪ Few fauna occupancy trends could be assessed due to lack of data, with mixed results from available survey data – for example, surveys showed Powerful Owl and Sooty Owl occupancy around Eden recovered significantly from a near zero base between 1988 and 2011, while the Greater Glider declined significantly in the same period. ▪ Invasive pest and weed species (particularly cats and foxes) and habitat loss and degradation (particularly from clearing and land use change) are identified as key threats to biodiversity. ▪ Candidate Old Growth forest was used as a surrogate for logging history and severity, and was found to not feature as strongly as expected in most fauna species occupancy or habitat models. Candidate Old Growth was positively associated with the distribution of four fauna species in north coast forests. ▪ Similarly, few flora species were found to have a positive association with 'undisturbed' sites mapped as Candidate Old Growth, inferring that few species have been adversely impacted by native timber harvesting up to 2000. However, it is noted that many species were recorded too infrequently for rigorous analysis. ▪ Nine rainforest and wet sclerophyll forest plant species, including three epiphytes, were identified as likely to be sensitive to timber harvesting, noting that harvesting is excluded within identified rainforest areas. ▪ The 2019-20 wildfires impacted on the habitat of 378 bird, 83 mammal, 254 reptile, 102 frog, and 15 freshwater fish species - 70 species had more than 30 percent of their habitat impacted by the fires, with 19 having more than 50 percent of their habitat affected. ▪ Twice as much suitable species habitat is now classed as impacted by high frequency fire.	▪ Combined effects of climate change and fire, along with pests and weeds, represent the most significant threat to the biodiversity of eastern NSW forests. ▪ Species occupancy modelling for future climate projections suggest that potential occupancy of 54 of 78 threatened fauna species assessed will decline by 2070; of these, seven species will be particularly affected. ▪ Suitable habitat was predicted to decline under projected 2030 and 2070 climate change scenarios ('warmer/wetter' and 'hotter/little change') for 14 of 24 threatened fauna species assessed ▪ For 81 climate-sensitive flora species, climate modelling predicted that 48 species will have less medium to high-suitability habitat by 2070 due to climate change, whereas 30 species will have more.

	Status and trend	Outlook
	▪ The 2019-20 wildfires impacted local koala populations - koalas were absent in some areas where high fire severity dominated the landscape, with localised recovery after a year.	
Soil resources *Concentrations have varied over time and space* *Analysis significantly improved knowledge base but more monitoring is needed*	▪ Modelled estimates of soil organic carbon concentrations have varied, with decreases in the mid-1990s followed by increases in mid-2010s. The significant fluctuations in this period are likely to have been driven by climatic conditions. ▪ Areas subject to increased ground disturbance from land use activity (particularly in forests in which grazing is permitted) have lower concentrations of soil organic carbon than less disturbed areas. ▪ Researchers modelled the likely relative loss of soil organic carbon during a fire event and found it to be substantially high, ranging between 40 and 60 percent. Post-fire recovery of soil organic carbon was estimated to be around 60 percent after 20 years, with full recovery after around 75 years. ▪ Soil carbon models for coastal NSW decline around the time of the 2019-20 wildfires, after reaching a high point around 2016-17. ▪ The researchers reported critical data gaps relating to soil health due to a lack of sustained monitoring.	▪ Further future decline in soil organic carbon due to climate change, with greatest losses in areas with currently high soil organic carbon stocks, such as the southern alps. ▪ Potential for ongoing cycles of decline in soil organic carbon if areas are subjected to repeated fire events and/or other disturbances (such as grazing, timber harvesting or land clearing) that prevent the recovery of soil organic carbon levels between disturbance events. ▪ A slight rise in soil pH (more alkaline) expected, again highest in the southern alps, affecting ecosystems that have established under particular pH ranges.
Forest catchments *Long term trend of declining flows* *Lack of data impacting water quality analysis* *Analysis significantly*	▪ Flows have been declining in forest catchments over the last 30 years, especially on the south coast of NSW. ▪ Over a third of the coastal forested catchments assessed showed significant annual flow reductions of 10 to 20 percent in this period. Wetter catchments and catchments with a greater percentage of area used for grazing experienced greater percentage decline in flow. ▪ At the catchment scale, historical changes in flow are generally more heavily affected by hydro-climatic drivers than fire events, although some impacts on streamflow due to fire events were observed.	▪ More frequent cycles of drought and recovery are likely to further exacerbate recent trends around declining flows. ▪ Ongoing declines in catchment flows are likely to have adverse impacts on forest health, groundwater recharge and water quality. ▪ Increased fire activity and intense rainfall events are likely to lead to more

	Status and trend	Outlook
improved knowledge base but more monitoring is needed	▪ There was a correlation between a larger proportion of undisturbed catchment and a greater flow reduction, however the flow reduction is also highly variable for catchments that are rarely disturbed by fire and harvesting. This suggests no clear link between the spatial differences in long-term flow trends and the history of fire and harvesting. ▪ With the currently available data, there is little evidence that the 2019-20 fire has a substantial impact on the quantity of streamflow at the catchment scale, compared with long-term historical conditions. ▪ Lack of data prevented analysis of water quality indicators.	erosion with major implications for water quality and waterway health.
Aboriginal values *Need for greater access and involvement in land management*	▪ There are significant knowledge gaps around Aboriginal cultural values due to Aboriginal peoples' lack of access or involvement in land management and custodianship ▪ The 2019-20 fires impacted many cultural values and practices – some cultural values have been destroyed or are at higher risk, for example scar trees, rock art and stone artefacts ▪ Except for Aboriginal managed lands, Aboriginal people are not adequately involved in land management and decision making, including identifying and managing cultural values. ▪ Proposal arising from case studies to pilot Whole-of-Country planning in collaboration with the Banbai Rangers and Guyra and Tamworth Local Aboriginal Land Councils.	▪ Cultural values at risk of damage or loss from increased fire activity and intense rainfall events, with concern that sites may be deregistered or devalued as a result. ▪ Opportunities for improved cultural values and outcomes through greater involvement in land management and decision making, including through expansion of Aboriginal-owned and managed tenures, specifically Indigenous Protected Areas, and Whole-of-Country planning processes.
Productive capacity and sustainability *Wood supply and sustainable yield forecasts reduced*	▪ The 2019-20 fires reduced the available wood supply across both public and private land, particularly on the South Coast where around 80 percent of net harvest area was affected. ▪ Short-term sustainable yield forecasts were revised to account for the impact of the 2019-20 wildfires given the loss of wood products and regrowth, with around 30 percent reductions for the South Coast and Tumut subregions.	▪ Increased fire activity is likely to impact harvest planning and sustainable yield. ▪ Climate change will challenge the effectiveness of fire hazard reduction burning.

	Status and trend	Outlook
Social and economic benefits *Forest-dependent employment differs significantly across NSW* *Interim method in place to determine forest dependent jobs* *Significant data gaps exist*	▪ Forest-dependent employment differs significantly across NSW, particularly in relation to direct and indirect employment related to forest management, production of timber and wood products, sporting, health, and fitness events, and organised and informal tourism and recreation activities. ▪ Typically, forest-dependent employment is greatest in forest areas located in closer proximity to major population centres. This is due to the intensity of use of the forest estate, both for timber harvesting and production purposes and for recreation and tourism activities. ▪ Data available on organised tourism and recreation activities in NSW forests provides a strong base for robust estimation of direct and indirect employment, however there are significant data gaps for informal tourism and recreation.	▪ Forests will continue to provide important social and economic benefits to NSW communities through the provision of employment. ▪ Challenges remain to accurately quantify forest-dependent jobs without further engagement with industry and commitment from NSW agencies.

Blueprint Institute

Branching out

Exploring Alternate Land Use Options for the Native Forests of New South Wales

Contents

About Blueprint Institute

Every great achievement starts with a blueprint.

Blueprint Institute is an independent public policy think tank established in the era of COVID-19, in which Australians have witnessed how tired ideologies have been eclipsed by a sense of urgency, pragmatism, and bipartisanship. The challenges our nation faces go beyond partisan politics. We have a once-in-a-generation opportunity to rethink and recast Australia to be more balanced, prosperous, resilient, and sustainable. We design blueprints for practical action to move Australia in the right direction.

For more information on the institute please visit our website: blueprintinstitute.org.au

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Attribution

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David is a public policy expert and leader with extensive experience managing large teams and providing advice across multiple portfolio areas to senior government ministers, heads of departments, c-suite business leaders, and university Vice-Chancellors. As CEO of Blueprint Institute, David leads one of Australia's newest and most dynamic public policy think tanks—crafting policy roadmaps for our political leaders in climate and energy policy, education, tax and fiscal policy, and productivity reform. His commentary has been featured in the Sydney Morning Herald, The Australian Financial Review, The Daily Telegraph, the ABC, and Sky News—as well as on numerous other outlets. Prior to joining Blueprint, David was Chief of Staff to the NSW Minister for Education and Early learning and led the crafting of significant pieces of education reform. He has also worked as a public policy adviser to the University of Sydney and as a business analyst in the private sector. David holds a Masters degree (MPhil) from the University of Cambridge in politics and international studies, and a first class honours degree from ANU. He is presently completing a PhD in public policy decision making processes at the University of Sydney.

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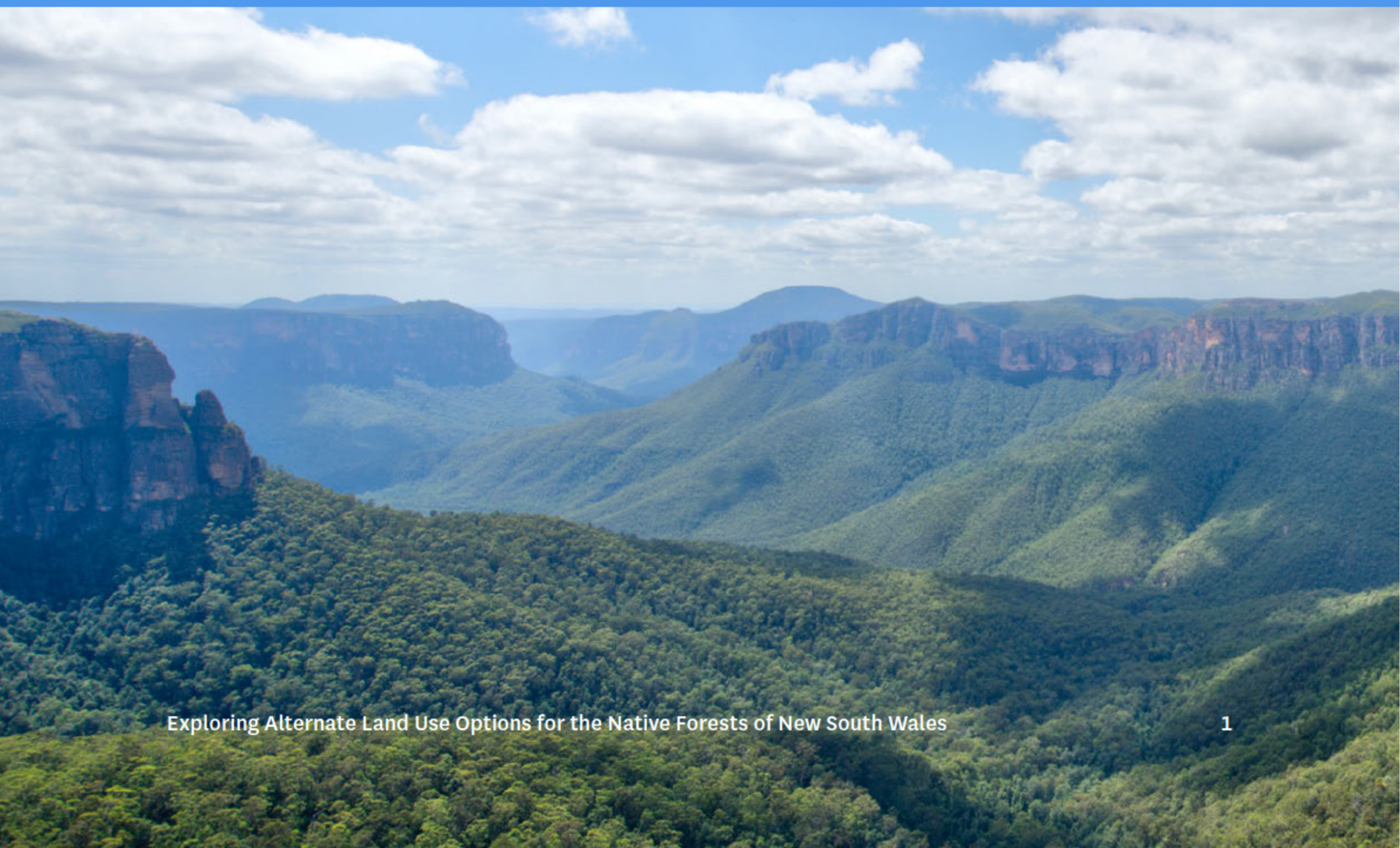
Executive summary

Australia is home to some of the world's most ancient forests. The benefits of native forests are extensive—they are efficient carbon sinks, they are amongst the most biodiverse environments on the planet, and they provide vast quantities of water (and preserve the quality of the water table).

This paper offers policymakers a blueprint for assessing the true value of our native forests. Recognising the inherent preferencing of the quantitative (particularly when it comes to Expenditure Review Committee processes), we conduct a comprehensive cost-benefit analysis of conserving the native forests of the Upper and Lower North East Regional Forest Agreement areas of New South Wales, also known as the North Coast. This piece of work builds upon Blueprint's previously published cost-benefit analysis of alternate land uses versus logging in Victoria's Central Highlands.

We assess the economic potential of native forest conservation by modelling the value of carbon sequestration and tourism against continued logging. Our findings demonstrate conclusively that there is no economic case for continued logging of native forests on the North Coast of New South Wales. As in the Central Highlands of Victoria, logging of native hardwood forest on the North Coast is a loss making enterprise, subsidised by Forestry Corporation of New South Wales' (FCNSW) profitable softwood plantation division, along with the taxpayer via periodic equity injections from the state government. Based on its own merits, we find that FCNSW's native hardwood division is not commercially viable.

Using cost-benefit analysis modelling we find that ending native forest logging in 2023–24 instead of 2039-40 (the date that the North East Regional Forestry Agreement is currently scheduled to expire), and instead utilising the land for carbon sequestration and tourism will deliver a net benefit valued at $45 million in present-day dollars. This includes the estimated cost of providing transitional packages to the industry as it shuts down, as well as the cost of breaking wood supply agreements that extend to 2028.



Were we to remove the cost of transitional packages and contract payouts from our cost-benefit analysis and assess the native logging industry on its own free market merits against alternate land uses for native forest, we find a net benefit of $260.1 million in ceasing logging immediately. By including a transitional package in our model, along with a range of other favourable assumptions, we, methodologically speaking, have given the logging industry 'the benefit of the doubt'—demonstrating that even when every conceivable dollar is counted in favour of FCNSW's native hardwood timber division, it nevertheless runs at a loss.

The native forests on the North Coast have significant capacity to immediately generate major alternate revenue streams that can replace revenue generated from logging. In particular, we find that managing the North Coast region in a manner consistent with conservation would abate an average of 0.45 million tonnes of carbon annually. This equates to a net present value of $174 million. Our analysis also indicates that increased tourism to the region could, over 17 years, provide a net present value of $120 million. In totality, from present to FY2040, using the forests of the North Coast for purposes other than logging will generate at least $294 million in revenue.

The next government-led five yearly review of the logging industry will commence in 2024, making now an ideal time for impactful analysis. We encourage the New South Wales Government and Opposition to enact the following recommendations

1. Immediately cease all government subsidies to FCNSW.
2. Create a 'natural capital' weighting that increases the Benefit Cost Ratio of native forests when Expenditure Review Committee decisions affecting them are made.
3. Legislate the end of native forest logging in New South Wales.
4. Expand land valuation methodologies to include carbon storage, tourism and water.
5. Expand hardwood timber plantations to meet hardwood demand.
6. Incentivise private investment in timber plantations.
7. Expand formal policy mechanisms aimed at conserving native forests.

Australian forestry

Native forestry in Australia is on the decline. This is a result of a combination of factors, including unsustainable harvesting practices, conservation concerns, market pressures, bushfires, and a decline in public support. Between 2008 and 2019 harvest levels from Australian native forests fell by over 50%. The native forestry industry has also been affected by the shift toward plantation-based forestry, which is significantly more productive—commercial plantations comprise only 1.5% of Australian forests, yet they generate 88% of Australia's wood supply.

State governments have tried to sustain the native forestry industry despite its deteriorating economic outlook, often incurring significant financial losses. Blueprint Institute's analysis has shown that immediately halting native forestry logging in the Central Highlands of Victoria—as opposed to the status quo of a delayed exit by 2030—will deliver a net benefit of $59 million in present-day dollars. Similarly, the Victorian Parliamentary Budget Office concluded that immediately ending native logging in the state would save taxpayers $192 million.

Sustainable Timber Tasmania (formerly Forestry Tasmania), ran at an alarming loss of $454 million over 20 years from 1997 to 2017. The Tasmanian forestry industry has been the beneficiary of almost one billion dollars worth of rescue packages in the form of state and federal grants. The hardwood native sector of Forestry Corporation of New South Wales has also generated consistent losses, recently calculated at $441 per hectare in 2021.

Due to these rapidly deteriorating financial results, some state governments have acted to phase out native logging. The Victorian government has committed to, but is yet to legislate, phasing out native logging by 2030. In Queensland, native logging is being phased out in the western, south-east, and eastern regions. In Western Australia, the government has recently announced plans to end native logging from 2024 and invest $350 million in softwood timber plantations to support sustainable jobs. Their September 2021 announcement argued:

> **The ever-increasing impacts of climate change, the importance of maintaining biodiversity and forest health, the need for carbon capture and storage, and declining timber yields mean that it is essential that we act now to protect Western Australia's forests.**

In New South Wales, there are no concrete plans, legislative or otherwise, to phase out native logging in a timely manner—despite extensive evidence that the native forestry division of the state owned Forestry Corporation delivers poor financial returns. In fact, in 2018 the Federal and New South Wales Government extended the Regional Forest Agreements in the state by 20 years.

New South Wales forestry

Over 50% of native forests in New South Wales, an area of approximately 29 million hectares, have been lost as a result of deforestation since 1750. This equates to an area roughly the same size as New Zealand. Of the remaining 25 million hectares, nearly a third is considered degraded. This mass deforestation is one of the major causes of species decline. Australia now has 1869 flora and fauna species listed as threatened with extinction. A recent study approximated that 244 threatened species in New South Wales were potentially impacted by logging between 2000 and 2022.

In addition to depriving native species of critical resources, such as food, shelter, and breeding areas, logging also necessitates the construction of road networks to transport timber from forests to processing facilities. These roads can provide easy access for invasive predators like cats, dogs, and foxes, as well as enable the spread of pathogens.

Since the late 1990s, New South Wales has undergone a transformation in its approach to forest management, claiming greater emphasis on the importance of ecologically sound practices. At the heart of this shift are the three Regional Forest Agreements established between the Commonwealth and New South Wales Government. These consist of The Eden Regional Forest Agreement, The North East Regional Forest Agreement, and The Southern New South Wales Regional Forest Agreement. The agreements attempt to provide a framework for the sustainable management of forests in New South Wales and regulate logging operations. In 2018 the Federal and New South Wales Government extended the agreements until FY2040. The agreements nominally run for 20 years, but can be extended indefinitely on a rolling basis for a further five years, provided native timber harvesters pass a five-yearly review. The next scheduled review is due to be conducted in 2024.

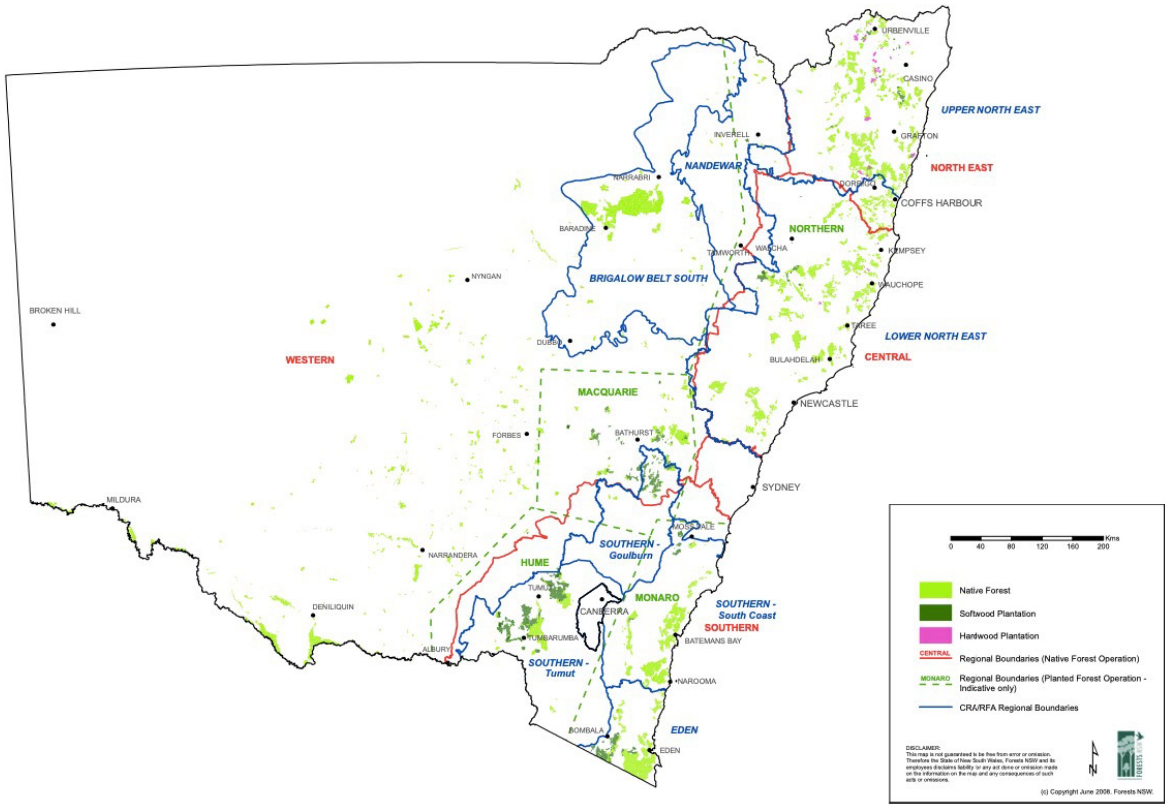


Figure 1 State forest regional boundaries and CRA/RFA regional boundaries
Source Forestry Corporation

Forestry Corporation of New South Wales (FCNSW) is the government body responsible for managing nearly two million hectares of state forest. Half of these forests are preserved for tourism, recreation, conservation, and agricultural uses. The remaining one million hectares are available for logging, of which approximately 30,000 hectares of native forests are harvested annually.

FCNSW segment their operations into a softwood and hardwood division. The softwood division is made up of exotic or non-native trees (predominantly radiata pine) harvested entirely from plantations. By contrast, although FCNSW currently manage a small area of hardwood plantation estate, the vast majority of hardwood timber is derived from native forests.

The past 20 years has seen a growing recognition of the importance of preserving native forests as biodiversity hotspots and carbon sinks. In particular, concerns have arisen over the detrimental effect of logging on native ecosystems. This has led to increased public scrutiny and calls for greater protection of native forests.

Correspondingly, since 1994, the size of the state forests under the management of FCNSW has shrunk by nearly 2 million hectares, primarily due to transfers of land to the National Parks and Wildlife Service. As a result, the volume of hardwood timber harvested by FCNSW has decreased significantly, falling from 1.3 million cubic metres in 2010 to around 939,000 cubic metres in 2017. Timber production further plummeted following the Black Summer bushfires to a low of 0.6 million cubic metres in 2020–21. This has placed significant strain on sawmills dependent on hardwood timber.

A significant amount of native forest is also held under private ownership. Prior to harvesting timber, landowners must acquire approval from Local Land Services in the form of a Private Native Forest Plan (PNFP) as well as a forest management plan. In 2021, there were approximately 580,000 hectares of private land that were covered by the PNFP. In 2022, the state government reformed Private Native Forestry Codes to support the growth of privately owned forests for timber production.

While there is a large area available for timber production on private land, mostly situated on the North Coast, the productivity of this land has been relatively poor to date. The New South Wales government attributes this to young regrowth in private forests being in a poor growing state. Other research has pointed to private landowners' lack of professional expertise and the inaccessibility of information on effective native forest management.

Losses in the hardwood sector

The hardwood and softwood division of FCNSW produce vastly different financial results. An inspection of historic data shows that the hardwood division—the vast majority of which consists of native trees with a small proportion of plantation estate—is being propped up by the far more economically viable softwood sector.

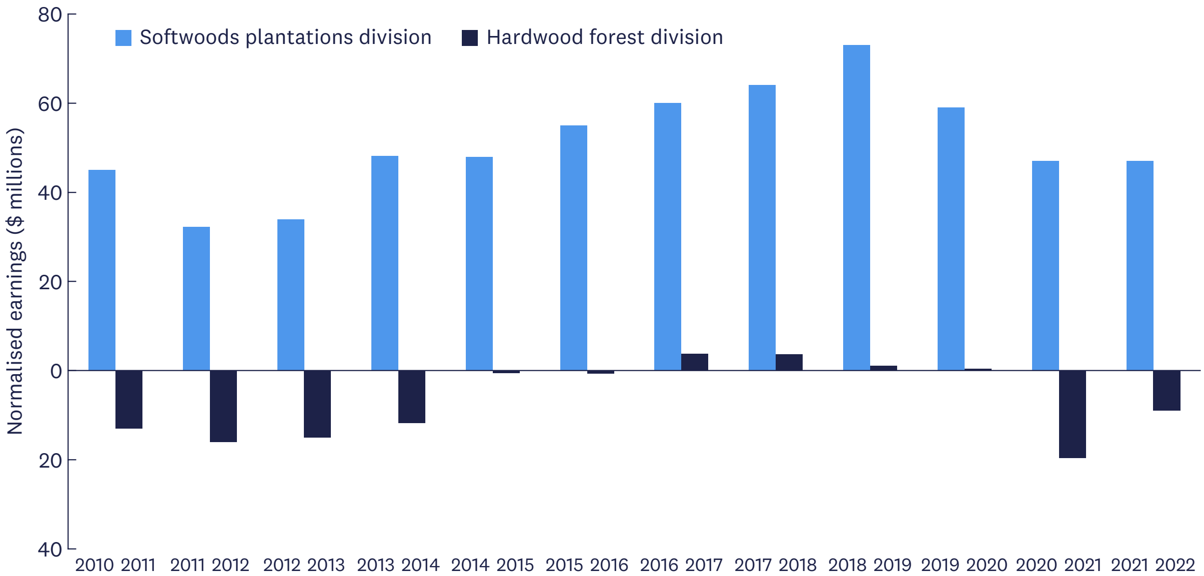


Figure 2 Normalised earnings of softwood plantations and hardwood forests (2010–2022)
Source Forestry Corporation

As shown in Figure 2, the softwood division of FCNSW reported total normalised earnings of $290 million from 2018 to 2022, with average annual earnings of $58 million. This is vastly superior to the hardwood sector, which even for the five years prior to the Black Summer bushfires was on average only able to achieve annual normalised earnings of a mere $1.4 million.

One may be tempted to attribute the hardwood division's troubles to extenuating circumstances. According to FCNSW's latest annual reports, the hardwood division incurred an operational loss of $28.6 million over the past two years, primarily as a result of bushfire and extreme wet weather events. A closer analysis reveals, however, that the hardwood division has endured long periods of financial loss predating the effects of the Black Summer bushfires. Between 2010 and 2014, the hardwood division lost $55.8 million.

The organisation underwent a major restructure in 2014, cutting costs by $5 million per annum. This allowed the hardwood division to achieve a very slight operating profit of $3.8 million for the first time in 2017.

While cost-cutting allowed the hardwood division to achieve a moderate fiscal turnaround, it is crucial to note that the fundamental nature of FCNSW's native forestry business in the North East RFA remains unaltered, with neither product, value, nor volume seeing any appreciable improvement. Any organisation can, to an extent, cut overheads to achieve a marginally better financial result, but without more substantial reforms it is unlikely such improvements will be sustainable nor repeatable.

Forestry employment

As it stands, the state-run native logging industry in New South Wales is not a substantial contributor to regional employment. According to their latest annual report, FCNSW has 562 full-time equivalent employees. Approximately 235 people are believed to be employed in the hardwood division, according to evidence given at the 2015 budget estimates.

If native logging were to stop, the positions that would be at greatest risk would be those that manage the timber sales, harvesting and hauling operations, and primary wood processors such as sawmills. The Northern region has the highest concentration of employees in these sectors, with the total number estimated to be around 590.

The hardwood sector has been in structural decline for some time, largely due to the introduction of more stringent forestry regulations. The reduction in wood supply has caused contraction in the processing industry. As less hardwood has become available, the number of people employed in hardwood sawmills has reduced. The majority of sawmill jobs are concentrated in several local government areas. To keep haulage costs down, sawmills tend to be located close to native logging operations. Australian census data shows declining employment figures in nearly every local government area of concern. For instance, within Clarence Valley, employment in wood product manufacturing fell by 23% from 2016 to 2021.

Despite the commonly reiterated political narrative, the forestry industry makes up a small, and in the case of wood manufacturing, declining share of regional employment. According to the latest census data, the percentage of people employed in the forestry and logging sector (which includes activities related to forest management, growing and harvesting) within the relevant Local Government Areas is between just 0.1% and 1.4%. The corresponding figure for people directly employed in wood product manufacturing (which includes those working in sawmills) is between 0.5% and 2.5%. Australian Bureau of Statistics data provides aggregate figures for those employed in both plantations and native forestry. Thus, the proportion of people directly involved in the native forestry sector of FCNSW would logically be less than these figures.

We are cognisant of the historical importance of the forestry industry—particularly the intergenerational employment opportunities it has offered to regional communities. It is vital that appropriate measures be taken to fairly compensate workers in the forestry and wood manufacturing sector in light of industry contraction. This is similarly the case in other states where employee support packages have been put in place to ease the transition following the ending of native forestry. We propose a similar transition package in New South Wales if native logging were to cease.

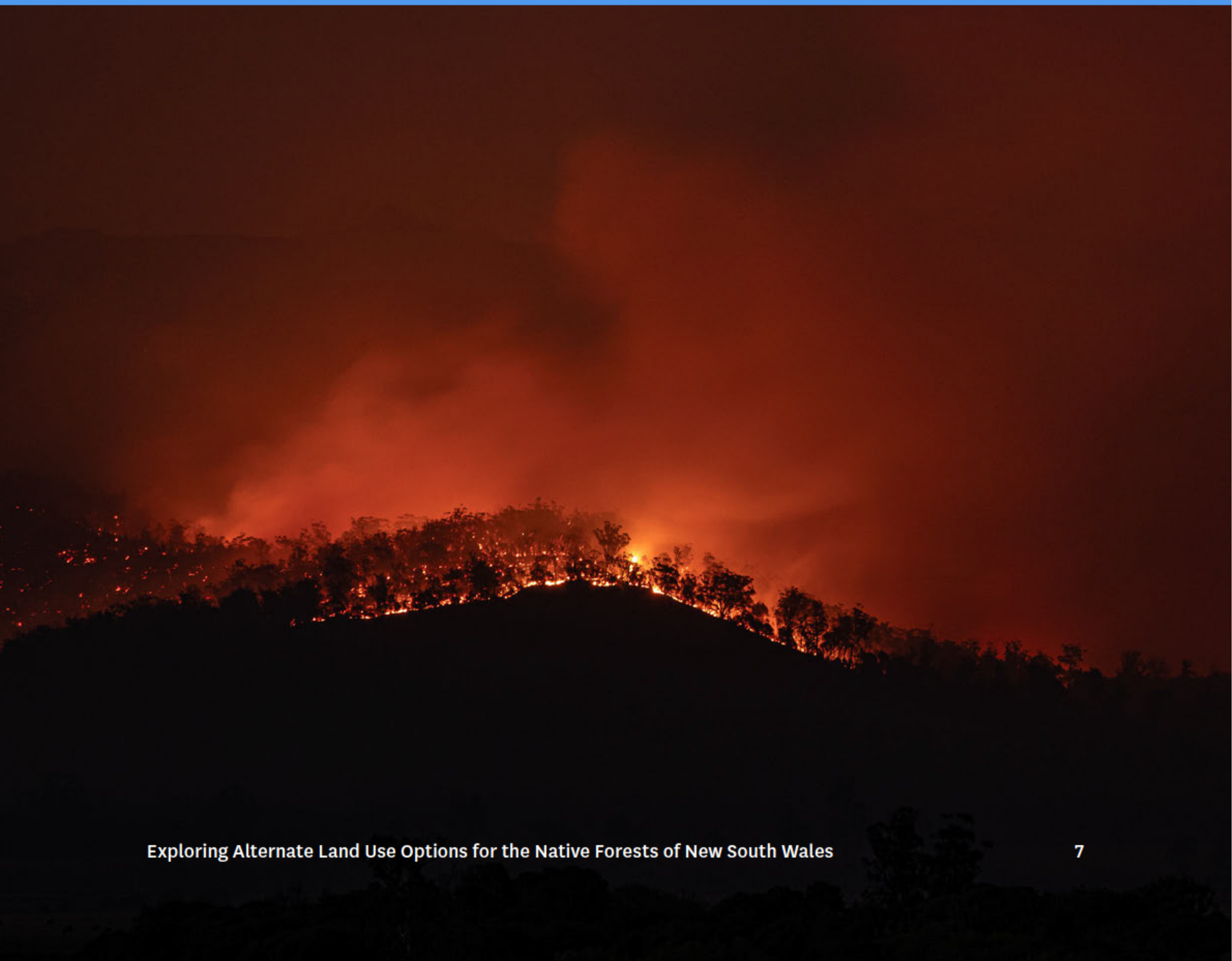
Fire

Several studies have shown that logging activities in forests can increase the severity of bushfires, particularly during extreme weather events such as those experienced during the Black Summer bushfires.

Logging has been shown to cause changes in the structure and composition of the forest, making it more vulnerable to fire. For example, logging can remove older, larger trees that are more resistant to fire and create a denser understory of small trees and shrubs, which can serve as kindling for fires. Logging can also lead to the accumulation of debris and dry vegetation on the forest floor, which can increase the intensity and spread of fires.

In New South Wales, the impact of the 2019-20 Black Summer bushfires ranged from an estimated 20% reduction in wood supply in the North Coast subregions to up to 90% in the South Coast subregion. Although the impacts on the North Coast were less severe, over 200,000 hectares of harvestable area were affected by the fires.

The relationship between logging and bushfire severity is complex, and can depend on a variety of factors such as the type and intensity of logging, the characteristics of the forest, and the weather conditions. However, it is clear that logging can increase the risk and severity of bushfires, and that managing forests in a way that reduces logging and promotes ecological resilience is an important step towards reducing the impact of bushfires.



Koala wars

Native forest logging has long been a contentious political issue in New South Wales. This controversy derives from conflating state subsidised native forest logging with private land clearing laws. Indeed, recalcitrant (in relation to logging) MPs on Macquarie Street frequently refer to the rights of rural landowners to manage their own farmland as reasons to oppose strengthening formal policy mechanisms to protect our native forests. Often forgotten is the fact that land clearing laws and government subsidy of native forest logging are two separate issues (even though both have a marked impact on ensuring the rehabilitation of koala populations).

The infamous 'koala wars' that almost split the Coalition and destroyed the Berejiklian government in 2019 had very little to do with native forest conservation practices, and more to do with National Party opposition to the State Environmental Planning Policy (Koala Habitat Protection) 2019 (SEPP44) which sought to protect koala habitat, and strengthen land clearing laws to protect other endangered species. The bill would have seen the protected tree species list increasing from 10 to 65—thus restricting the types of land that could be cleared privately.

Deputy Premier and Nationals Leader at the time John Barilaro claimed that the proposed bill undermined the ability of farmers to manage their own land. Barilaro then threatened to have the Nationals withdraw from the Coalition agreement with the New South Wales Liberals if the SEPP proceeded. Whilst Barilaro eventually backed down in the face of Premier Berejilklian standing her ground, the SEPP was watered down, and the issue remains contemporaneous.

Just prior to the 2023 election, the Nationals attempted to introduce a new private native forestry bill to make it easier for farmers to log native koala habitat. The bill proposed to remove the powers of local councils to limit native forest logging or implement environmental controls to protect threatened species within their region—handing over powers to private landowners. The bill was once again quickly withdrawn following threats of a revolt from Coalition members, including Nationals member for Tweed Geoff Provest—whose electorate was decimated by the recent floods in Northern New South Wales.

Study area—North East New South Wales

The economic analysis used in this study focused on the native forests of the North East region of New South Wales. This region comprises the Upper and Lower North East Regional Forest Agreement areas (Figure 3).

Within the North East Regional Forest Agreement area, there are around 836,000 hectares of native forests. The species used for timber in the region are: Blackbutt (E. pilularis), Spotted gum (C. maculata), Blue gum (E. saligna), tallowwood (E. microcorys), brush box (Lophostemon confertus), and New England species.

However, only 355,000 hectares are available for native timber production. The rest of the forests are reserved for conservation purposes. There are also 60,000 hectares of plantations in North East New South Wales—34,000 hectares are managed for hardwood and 26,000 hectares for softwood.

FCNSW sells native timber to wood processors under long term contracts or Wood Supply Agreements. In June of last year, nearly all Wood Supply Agreements on the North Coast were awarded five-year extensions until 2028 by the agricultural minister—much to the dismay of environmental groups.

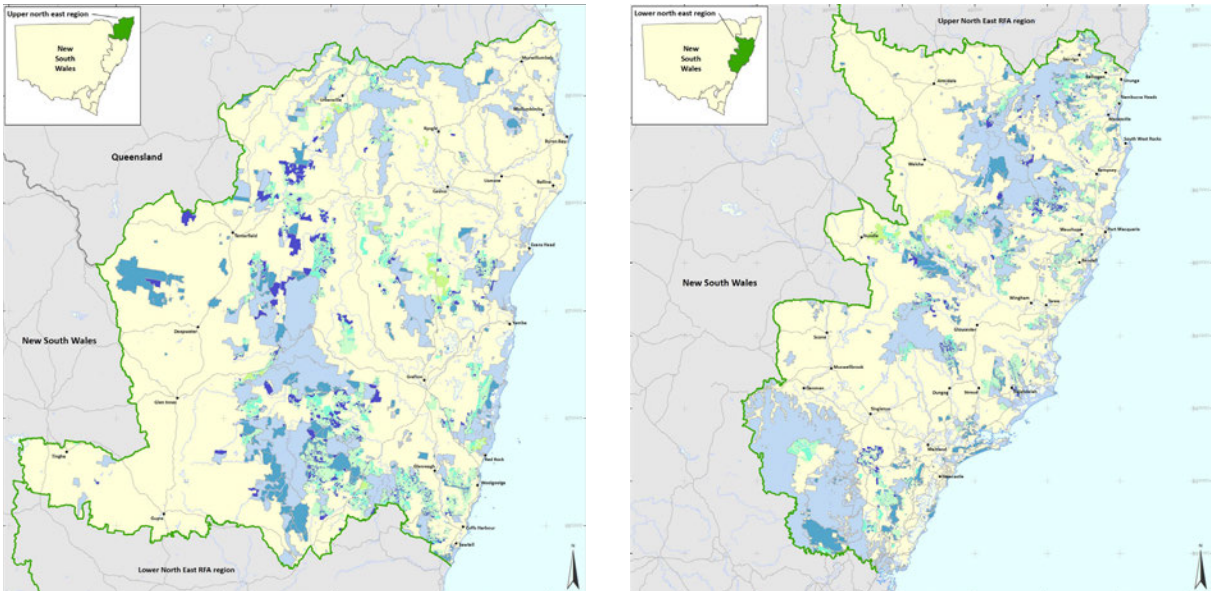


Figure 3 Upper and Lower North East Regional Forestry Agreements
Source ABARES

Plantations in New South Wales

Plantation logs are an economically superior alternative to native logging. They account for 88% of Australia's log production, despite occupying a fraction of the land area available for native forest harvesting.

Furthermore, as plantations are intensively managed, they are considerably more efficient and productive than native logging operations. Plantations provide various environmental benefits, such as carbon sequestration and biodiversity conservation. Notably, softwood timber generated by plantations emits 60% less greenhouse gas emissions compared to hardwood native timber.

Contrary to popular belief, native logging is not essential to supply the domestic construction industry. According to FCNSW's most recent sustainability report, as seen in Figure 4, at least half of the timber harvested from native forests is pulpwood and low quality logs. Pulpwood is a term used to describe trees that are used in the production of paper.

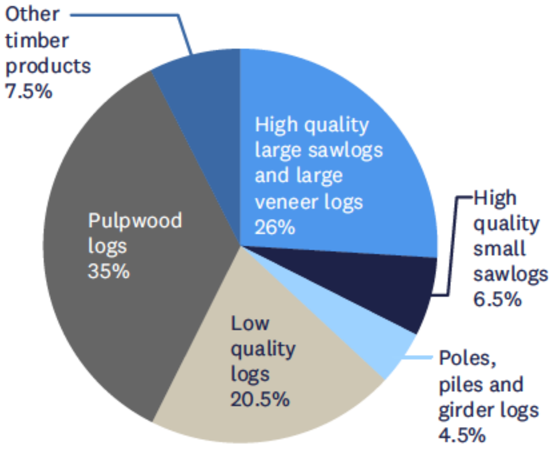
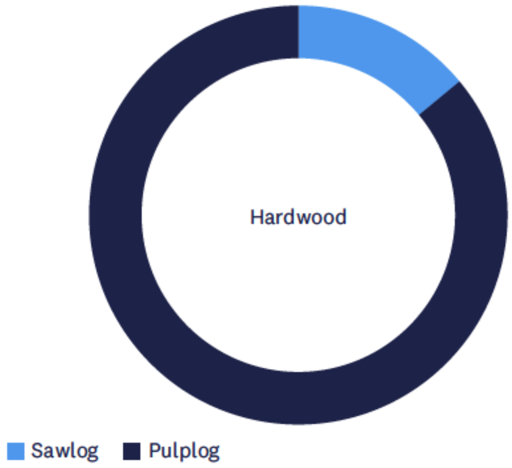


Figure 4 Distribution of sawlog production by type (2021–2022)

Source Forestry Corporation

Most of the timber that is used in housing is softwood sawlog sourced from plantations. As Figure 5 indicates, sawlog production makes up 97.5% of the softwood plantation estate. In contrast, hardwood plantations predominantly yield pulplog, with this making up 86% of supply.



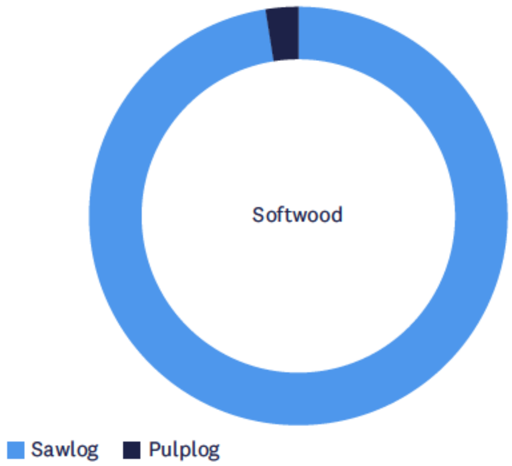


Figure 5 Sawlog and pulplog proportions for softwood and hardwood plantations in Australia (2021)

Source ABARES

Lack of investment in new plantations over the past several decades, as well as more stringent native forest regulations, have placed significant strain on the supply of both hardwood and softwood timber.

Between 1975 and 1990, softwood timber plantations in Australia grew by an average 33,000 hectares annually. However, this level of growth has since stagnated, with the total area remaining consistent at approximately one million hectares since the late 1990s. Evidence given to the 2022 industry inquiry into the long term sustainability and future of the timber and forest products industry indicated that the growth in softwood plantations has failed to keep up with both population growth and timber demand in the last 15 years. The former government's Home Builder stimulus package further compounded the timber shortage, as demand for construction materials increased far more rapidly than expected.

Hardwood plantations declined by 10% from 2014–2015 to 2019–2020. This decline has primarily been driven by the collapse of Managed Investment Schemes (MIS). During the late 1990s, the Nationals were seeking to bolster plantations in response to the decline of the Tasmanian timber industry. Their solution was to introduce an arrangement whereby investors were offered generous tax incentives to participate in agribusiness schemes.

In response, companies prioritised investment and expansion in short rotation hardwood pulplogs, which led to a boom in the industry. However, most of these forestry MIS companies collapsed around 2009 due to the global financial crisis. Many of the hardwood plantations previously managed under MIS have since been converted to other land uses, such as agriculture. This trend was particularly pronounced within the North Coast, where hardwood plantations have declined by over a third since 2009–10.

The decline in hardwood plantations can also be attributed, in part, to the fact that trees used in softwood plantations, like pine, are fast-growing and can tolerate a wide range of conditions, making them more suitable for plantation forestry. Indeed, softwoods tend to have a shorter time to maturity compared to hardwoods, which means they can be harvested and replanted more frequently.

The constraints affecting the supply of both hardwood and softwood were, of course, exacerbated by the Black Summer bushfires, which affected approximately 830,000 hectares of native state forests, as well as 62,000 hectares of state timber plantations in New South Wales alone. The availability of softwood sawlog timber has been forecasted to remain short until at least 2035.

During 2022, the federal government announced an $86 million dollar investment to expand the plantation sector. According to the latest budget papers, Labor is set to continue this policy. Whilst increased investment in plantations is necessary to meet the growing demand for sustainably sourced timber, the capital cost of acquiring additional land is considerable.

Previous studies indicate that a substantial expansion of the hardwood plantation sector, to the tune of 33,000 hectares, would require an initial investment of $165 million for land and establishment costs. The whole-of-life expenditure for such an expansion, estimated over 25 years and assuming a 7% discount rate, would cost $233 million in present-day dollars. The same study also argued that an additional 33,000 hectares of softwood plantation would come with a price tag of $204 million over 30 years, assuming a 7% discount rate.

How farm forestry can meet growing demand

One of the ways to alleviate timber supply issues, as well as avoid the high capital costs of purchasing additional land, is to encourage the uptake of farm forestry.

Over half of the native forests on the North Coast of New South Wales (3.4 million hectares) are in private ownership. Much of these are currently used for livestock grazing. Graziers generally clear land, meaning they remove most or all of the trees.

Farm forestry, or silvopastoral systems (SPSs), refer to the practice of deliberately managing both livestock and trees and aims to optimise land productivity within a given area. Silvopastoral systems present a promising opportunity to improve the financial outcomes of farms by diversifying their income streams.

Silvopastoral systems have been shown to increase fertility of the soil, boost growth rates and improve the quality of life of the animals by providing shade. If graziers sustainably harvest native timber or convert part of their land into plantations, these trees would not only sequester methane emissions from cattle, but also alleviate some of the strain on timber supply.

A 2020 study affirmed that approximately 525,600 hectares of privately owned land within the North East Regional Forestry Agreement met the necessary preconditions to be of high harvestable quality.

The greatest barrier preventing the uptake of farm forestry amongst landowners may be a byzantine tangle of red tape that has led to confusion. An investigation by an independent journalist last year found that graziers believe they are currently stymied by restrictive codes that prohibit timber harvesting in conjunction with livestock production. The article asserts that the Private Native Forestry code forces graziers to choose one or the other.

Blueprint's own investigations with an official at New South Wales Local Land Services, however, contradict this claim. Instead, the office stated that timber harvesting in conjunction with livestock grazing has always been allowed, subject to certain regulations.

The government has introduced an $86 million grant program over five years to encourage new forestry plantations. We propose that this be made available to landowners to establish silvopastoral systems. At the same time, the government must work closely with landowners to better communicate exactly what is and is not allowed under the Private Native Forestry code in order to enable farm forestry to reach its full potential.

A cost-benefit analysis of native logging in the North East RFA region

The focus of Australian policymakers in land-use assessment has been overly myopic, limiting our ability to fully leverage the potential of our distinctive ecosystems for sustainable economic prosperity.

In addition to their commercial value, forests offer a range of intangible benefits that should be taken into account. These include improvements to social, psychological, and physical well-being, safeguarding habitats for endangered species, and enhancing biodiversity. Whilst these benefits should arguably be priced into any economic analysis, due to their intangible nature, it is difficult to project an accurate price for a subjective value that may ultimately compromise the accuracy of the tangible cost analysis.

We have thus omitted intangible benefits and costs in our overall cost-benefit analysis. Yet even when considering land-use scenarios from a purely economic perspective, our cost-benefit analysis concludes that ending logging in the region would deliver a social benefit of $45 million in present day dollars compared to the business as usual case of continuing to log until FY2040.

Benefits	
Avoided costs from logging	$725 million
Carbon sequestration value	$174 million
Tourism revenue	$120 million
Total	**$1,020 million**
Costs	
Forgone logging revenue	$744 million
Costs for developing tourism	$15.7 million
Industry adjustment package	$215 million
Total	**$975 million**
Net present value (Benefits less Costs)	**$45 million**
Benefit-cost ratio	**1.05**

Table 1 Cost-benefit analysis comparing business as usual to ceasing native forestry in 2023

Source See Appendix

Notes Net present value factors in a seven percent discount rate. For technical details on our cost-benefit analysis, refer to the Appendix at the end of this paper.

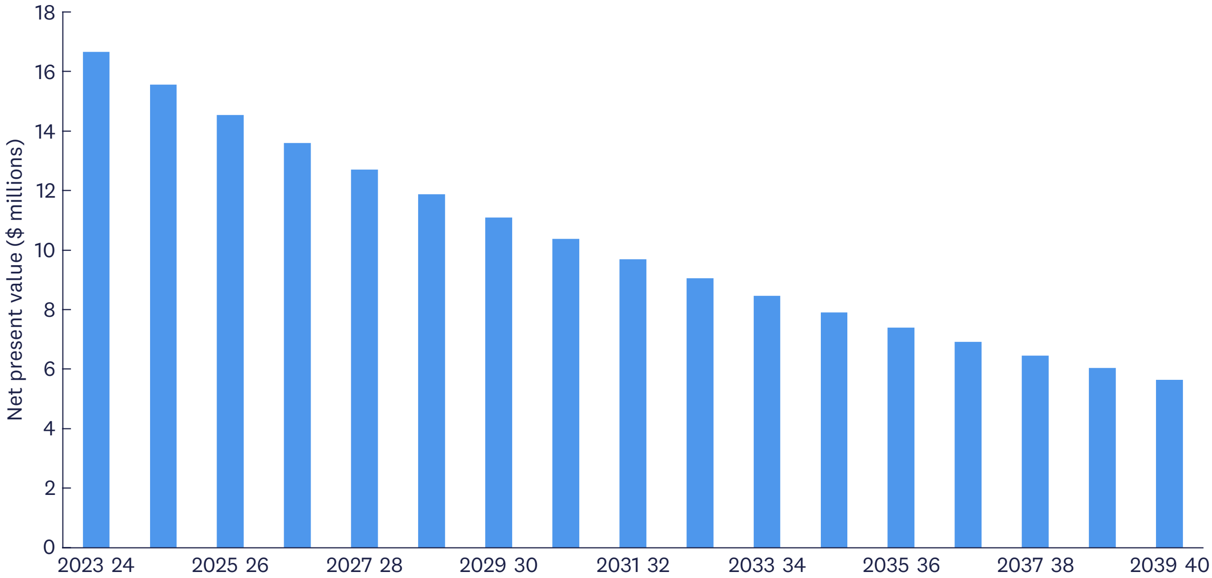


Figure 6 Net present value of the cost-benefit flow in cessation of logging scenario (2023–2040)
Source Blueprint Institute analysis
Note A seven percent discount rate is applied.

Carbon

Carbon abatement from stopping logging across 2023–40 (tCO2e)	7.65
Australian carbon credit unit spot price (per tonne of CO2, March 2023)	$36.65
Net present value	$174 million

Table 2 Net present value of carbon abatement due to cessation of logging (2023–40)

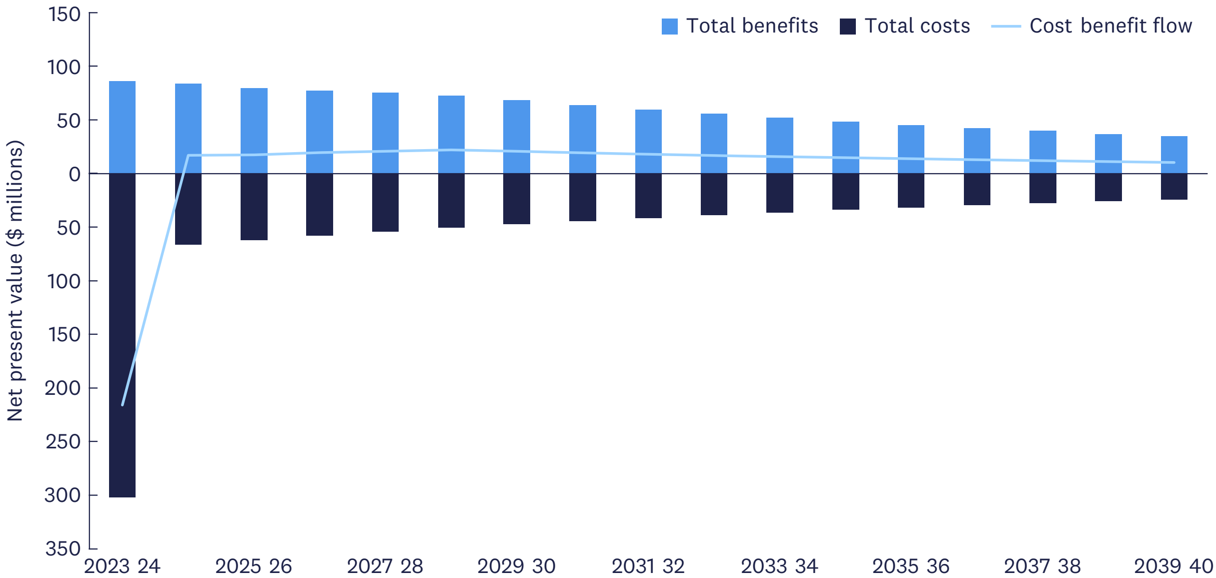


Figure 7 Net present value of carbon abatement due to cessation of logging (2023–2040)
Source Blueprint Institute analysis
Note A seven percent discount rate is applied.

Managing the North East RFA region in a manner consistent with conservation would abate an average of 0.45 million tonnes of carbon annually. This equates to a net present value of $174 million if logging were to stop now relative to business as usual up to FY2040. This figure is based on the March 2023 Australian carbon credit unit spot price of $36.65 per tonne, and a seven percent discount rate.

Forests play a crucial role in mitigating climate change by sequestering carbon dioxide from the atmosphere and storing it in the form of organic matter. Across Australian forests there are over 21,949 million tonnes of carbon stored, and, in New South Wales, over four million tonnes of carbon are stored across the native forests and plantations that FCNSW manage. By logging native forests, this carbon is released back into the atmosphere, contributing to greenhouse gas emissions and exacerbating climate change. Assessments of carbon stocks across New South Wales forests reveal a net loss of 164 million tonnes of carbon between 1990 and 2020.

Similar research has been done in the Southern and Eden RFA regions in New South Wales, showing that 0.95 million tonnes of carbon dioxide equivalents would be saved each year if logging stopped in these regions. This is 3.4 times more carbon abatement projected per year compared to the largest Emission Reduction Fund project.

In addition to the environmental benefits of preserving native forests, there are also economic benefits associated with carbon. Carbon credits can be generated by projects that preserve and enhance carbon stocks in forests, and these credits can be sold in international carbon markets as a way to finance conservation efforts. Although in Australia, this only applies to reforestation—the process of replanting trees in areas that have previously been cleared—the social value of carbon abatement nonetheless remains.

A common criticism of attempting to value carbon abatement is that it does not consider second-order effects. A sudden cessation in native timber logging could result in considerable carbon leakage as the industry could potentially be compelled to import timber to compensate for the lack of hardwood supply. Thus, deforestation could merely shift offshore to a country with far less scrupulous environmental regulations.

The change in carbon stock used in our study, therefore, was based on a paper that took carbon leakage into account. Notably, when using the life cycle assessment—the best carbon accounting framework to assess actual atmospheric impacts—findings showed that conserving native forests in New South Wales was not the most optimal outcome.

The paper notes that while managing native forests exclusively for conservation would result in additional carbon abatement, it was not the optimal result. Rather, continuing to log while also processing an additional 50% of the residue currently dumped at harvesting sites into pulp resulted in the most carbon abatement. This scenario would arguably maximise carbon abatement by avoiding the importation of pulp from other countries with less stringent environmental regulations.

It is not clear that processing more residue along the North Coast is economically feasible, however. Research has shown that utilising an increased proportion of native residue as part of forestry management is potentially uneconomic because of costly extraction and transportation—particularly in our study region, where the remaining native forest harvesting sites are relatively far away from processing facilities. The facts on the ground also speak for themselves—after all, if there was money to be made from hauling and processing a greater volume of residue into pulp, it is curious that profit-seeking firms have thus far chosen not to do so.

The problem of carbon leakage could also be addressed from another angle. Specifically, if commercial plantations were increased in the region to account for the loss of timber from native forests, the amount of carbon leakage would be reduced.

Plantation expansion would also increase the average carbon storage in woody biomass and contribute to Australia's emission reduction targets. Furthermore, plantations have the economic advantage of gaining tradable carbon credits, which only 10% of FCNSW plantations currently qualify for.

Tourism

Our analysis indicates that increased tourism to the region through FY2040 could provide a net present value of $120 million at a seven percent discount rate.

While we are proposing conserving the entire 355,000 hectares currently available for native timber logging in our study area, our scenario calls for an initial allocation of 100,000 of those hectares to develop recreation facilities to encourage tourism. We estimate that an initial upfront investment of $15.7 million would be required to develop the proposed facilities. This would include the creation of the 50km walking trail, a 900km boundary as well as the construction of park infrastructure such as campsites, pathways, signs, and car parks. Cost estimates for each of these items are detailed in the appendix. Construction would take place over five years.

Ongoing costs related to park maintenance and staffing would be approximately $2.2 million annually. We also note that the New South Wales government already allocates significant annual grants ($25 million in FY2022) to FCNSW for forest management services such as "provision of recreation facilities, education and advisory services...,flood stabilisation, tourism precincts..., light fleet fire spray protection, and strategic fire trails." We assume these expenditures would continue, albeit adjusted to focus primarily on conservation.

Tourism plays a crucial role in the New South Wales economy, contributing $37.1 billion in 2019-2020 and employing over 256,000 people. Unsurprisingly, COVID-19 and the Black Summer bushfires caused significant disruption to the sector, leading to a decline in tourism consumption of 20.5% compared to the previous year. There was also a significant contraction in tourism employment of 13.5% compared to 2018-19.

Visitation to national parks in New South Wales has been growing annually, increasing by 58% in the decade 2008-2018 (Figure 9).

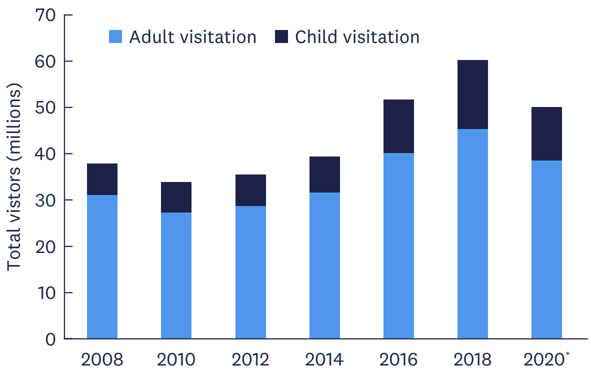


Figure 9 Visitation in New South Wales national parks

Source New South Wales Department of Planning and Environment

*Visitation in 2020 was impacted by major wide-spread disruptions, including natural disasters and the COVID-19 pandemic.

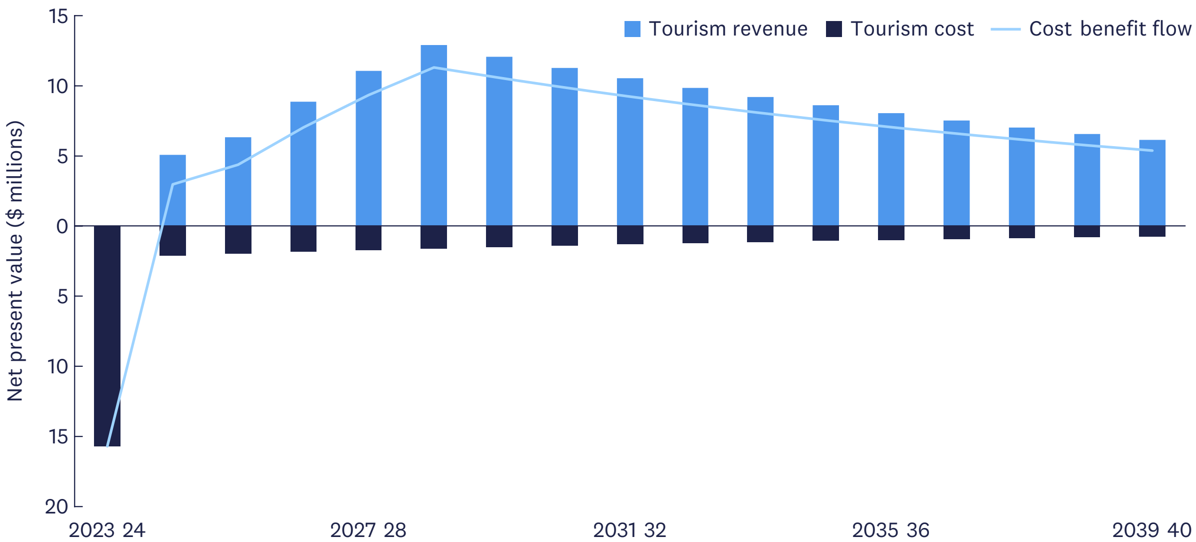


Figure 8 Tourism cost-benefit flow (2023–2040)

Source Blueprint Institute analysis

Note A seven percent discount rate is applied.

Although the pandemic predictably caused a decrease in visitation, the value that people place on the natural environment has risen since the lockdowns began. The results of a government survey show that on average, 45% of New South Wales residents reported an increase in their use of public spaces and parks following the pandemic, with parks and walking tracks being the two most appreciated public spaces.

Furthermore, nature based outdoor activities contributed $6.7 billion to the state's economy in 2016. In addition to these substantial economic contributions, nature based activities also offer social, psychological, and physical well-being benefits—resulting in $480 million in avoided healthcare system costs annually in New South Wales.

Access to outdoor space is key to taking advantage of these benefits. The North Coast of New South Wales attracted over 10 million visitors in 2022. Preserving the area currently being used for native timber harvesting provides the region with a great opportunity to capitalise on outdoor recreation.

The North Coast is also one of the last strongholds for koalas, with numbers estimated to be between 15,000 to 28,000. This is a huge asset for the region in generating tourism, with koalas being seen as the quintessential icon of Australia. Preserving the forests gives the dual benefit of providing more accessible outdoor space, whilst also expanding the potential available habitat for koalas. Unfortunately, the koala population in the region has declined by 30% following the Black Summer bushfires and is now an endangered species. To reverse this trend, it is imperative to protect and restore the koala habitat. Studies have indicated that, without additional conservation efforts, the koala population is likely to continue declining over the next 20 years, and current management plans may be insufficient to prevent their extinction. Conserving the native forests would secure an additional 355,000 hectares of land for the koala population in the region.

Limitations

Status quo

Our effort to value FCNSW's native forestry activities along New South Wales' North Coast involved significant methodological challenges. FCNSW's annual reports only provide detailed financial data for their activities in aggregate. This presents an obstacle as FCNSW is effectively comprised of two separate firms operating under two very different financial realities: the profitable softwood division, and the loss-making hardwood division.

When possible, instead of relying directly on FCNSW's annual reports, we derived our projections from other sources such as FCNSW's sustainability reports, in addition to reviews of FCNSW's operations—required periodically by law—conducted by independent organisations with access to proprietary FCNSW data.

For example, our projection of future high quality native timber harvest levels in the North East RFA was based on an average of predicted future sustainable volume found in FCNSW's sustainability reports, and similar data found in an analysis by the Sustainable Yield Review conducted after the Black Summer bushfires. In this case, our long-term annual harvest projections of 225,000m^3 of high quality sawlog, 143,000m^3 of high quality sawlog, and 41,000m^3 of pulplog are extremely likely to be significant overestimates.

Even before the Black Summer bushfires, FCNSW had not been able to consistently achieve our allocated harvest levels. Post-bushfires, in FY2022, harvest levels for high quality sawlog were just 105,000m^3, and long-term sustainable yield for high quality sawlogs was predicted to be below 200,000m^3 through FY2040. Our overestimates were intentional, as we wanted to show that even overly optimistic projections leave native timber harvesting in the North Coast at an operational loss.

Lastly, as the mills in the region are privately held entities, financial data on their operations were publicly unavailable. Thus, we were unable to include projections of the foregone revenue and avoided costs due to any mill closures in the region in the event native timber logging ceases.

Nevertheless, we have included the cost of an industry transition package similar in scale to those implemented in Victoria and Western Australia. The transition package includes redundancy and retraining cost for all employees who work in harvest/haulage and the mills, compensation payments for mill plant and equipment redundancy, the cost of wood supply agreement buyouts, and a sizeable allocation for regional economic diversification. The total cost of this transition package for the region is approximately $215 million. Detailed information on the derivation of this cost is available in the appendix.

Carbon

The net present value of additional carbon sequestration, in the event native timber logging on the North Coast ceases immediately, varies substantially depending on the carbon price used (Table 3).

Carbon price	Net present value of additional carbon sequestration
ACCU spot price	$174 million
Emissions Reduction Fund average price	$93 million

Table 3 Net present value of carbon abatement should North Coast native forests be managed exclusively for conservation, by carbon price (March 2023)

Source Australian Carbon Credit Unit, Emissions Reduction Fund, Blueprint Institute Analysis

We have elected to use the higher Australian Carbon Credit Unit spot price in our cost-benefit analysis as it is a marginal price, as opposed to the Emissions Reduction Fund average price.

Our estimate of annual carbon abatement was inferred from a 2016 study that projected an average of 0.45 million tonnes of carbon abatement annually over a 65-year period. We made the key assumption that the annual 0.45 million tonnes of carbon abatement would be consistent across the 17-year time frame as well.

Sensitivity analysis

We conducted a sensitivity analysis to ensure our results were robust to variance in discount rates, timber prices, and harvest volumes. Since our baseline harvest volume projection was already above the long-term projected sustainable yield of around 200,000m³ of high quality sawlog per year, we have only conducted a sensitivity analysis with respect to low future logging volumes (Table 4a, 4b, 4c).

Low discount rate	Base discount rate	High Discount rate
5%	7%	9%

Table 4a Sensitivity analysis—Discount rates
Source Blueprint Institute Analysis

Timber types	Low future logging volume (m³)	Low timber price (-15%)	High timber price (+15%)
High quality sawlog	175,000	$177/m³	$240/m³
Low quality sawlog	111,000	$94/m³	$127/m³
Pulplog	32,000	$72/m³	$97/m³

Table 4b Sensitivity analysis—Timber outputs
Source Blueprint Institute Analysis

	Baseline (7% discount rate)	Five percent discount rate	Nine percent discount rate	Low future logging volume	Low timber price (-15%)	High timber price (+15%)
Benefits (millions)	$1,020	$1,160	$905	$858	$1,020	$1,020
Costs (millions)	$975	$1,074	$894	$809	$863	$1,086
Net present value (millions)	$45	$87	$11	$49	$157	-$66
Benefit-cost ratio	1.05	1.08	1.01	1.06	1.18	0.94

Table 4c Sensitivity analysis—Results
Source Blueprint Institute Analysis

In all cases, except for the high timber price scenario, the net present value of immediately ceasing native timber logging remains positive, indicating our results are robust. Relative to the baseline, there is minor variance in results in response to differing discount rates and logging volumes.

Our results are considerably more sensitive with respect to variance in timber prices. A substantial increase in timber prices in the range of 15+% does tip the net present value of ceasing native timber logging into the negative. However, the significance of this finding should not be overstated.

The baseline timber price we used coincided with the peak of the inflationary cycle and may have already moderated substantially due to lower fuel prices. It is extremely unlikely that timber prices jump another 15+% from our already inflated baseline and remain permanently elevated across the 17-year timeframe of our analysis. In addition, we have also made a range of assumptions favourable to FCNSW's bottom line throughout the cost-benefit analysis—an adjustment of those assumptions to more realistic levels could easily return the net present value calculation under high timber prices to a positive number.

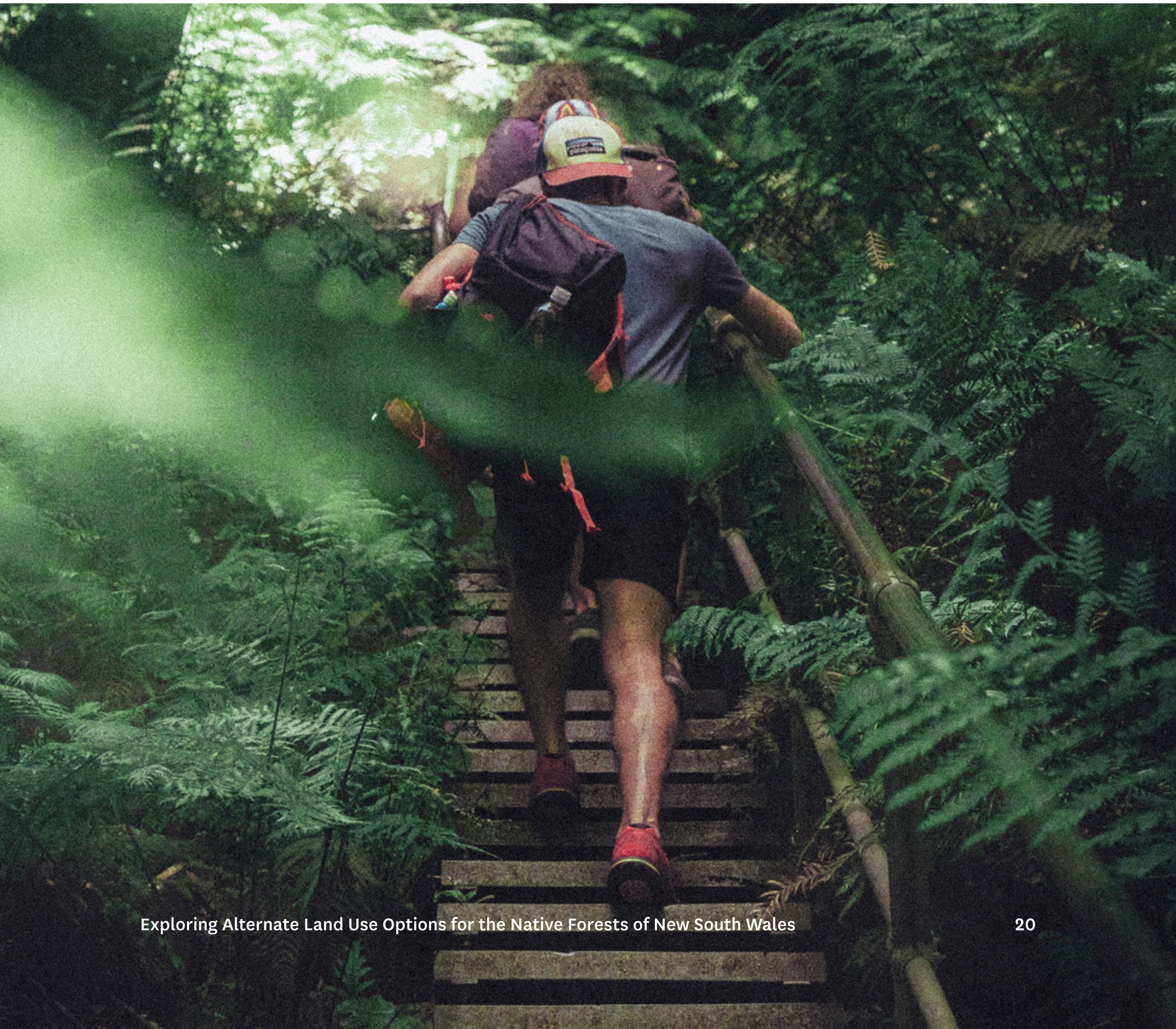
Tourism

The cost of building park infrastructure was derived from relevant case studies, with prices adjusted for inflation. We acknowledge that the case studies used are not directly comparable, and that, as a result, these costs should be interpreted as estimates.

Data was taken from Tourism Research Australia's National Visitor Survey to ascertain the average expenditure per trip per night in Northern New South Wales—resulting in an estimate of $210 per night.

Again, we acknowledge that this estimate may have a wide error margin. There are idiosyncratic spending choices at play—for example, national park campers are likely to spend differently to those staying in other accommodation. Also, as the Northern New South Wales region is home to many other popular tourist destinations, such as Byron Bay, it is plausible that travellers may visit the national park without staying overnight.

Thankfully, since our projections for tourism revenue were relatively small in scale in the context of the entire cost-benefit analysis, even a substantial cut in tourism revenue in the order of 25% does not change the ultimate conclusion of the analysis—that FCNSW's native forestry activities should cease.



Appendix

Modelling for status quo of logging through to FY2040

Our status quo scenario assumes continued native timber logging in the area defined by the North East Regional Forestry Agreement through the present day to FY2040, at which point the RFA expires.

Our projection of future high quality native timber sawlog harvest levels in the North East RFA was based on the predicted long-term average of future sustainable harvest volume, found in FCNSW's sustainability reports, and similar data sourced from a separate Sustainable Yield Review analysis, both produced after the 2019–20 bushfires (see Table 5).

It is our assessment that it is highly dubious that the projection of 225,000m³ of high quality sawlog yield is met, especially in the short term, due to the lingering effects of the Black Summer bushfires. Nevertheless, in order to maintain consistency with our overall philosophy of affording FCNSW the most favourable assumptions possible, we have elected to assume an improbable immediate rebound in harvest yield. This assumption errs on the side of a greater volume of native timber harvesting, thus inflating FCNSW's revenue and profit, particularly in the short term.

Projections for the volume of low quality sawlog and pulplog (see Table 5) were derived from the historical relationship between high quality sawlog, low quality sawlog, and pulplog yield. Specifically, our analysis found that high quality sawlog on average accounted for approximately 55% of total yield, while low quality sawlog accounted for 35%, and pulplog 10% of total yield.

Price estimates for hardwood native timber were calculated using data from the New South Wales Department of Primary Industries and Indufor, inflated to 2023 price levels using the producer price index for wood product and pulp, paper, and converted paper product inputs (see Table 6).

	High quality sawlog (m³)	Low quality sawlog (m³)	Pulplog (m³)
North East RFA	225,000	143,000	41,000

Table 5 Annual sustainable yield projections in North East RFA (2023–40)
Source FCNSW Sustainable Yield Review, FCNSW 2021-22 Sustainability Report, Blueprint Institute analysis

High quality sawlog (m³)	Low quality sawlog (m³)	Pulplog (m³)
$208	$110	$84

Table 6 Average price of hardwood native high quality sawlog, low quality sawlog, and pulplog (2023)
Source New South Wales Department of Primary Industries, Indufor, Blueprint Institute analysis

Cost projections for harvesting operations were based on the limited disaggregated data publicly available for FCNSW's hardwood division, published in their annual financial reports. Given that the only disaggregated information available was revenue and normalised profit, we based our future cost projections on the hardwood division's average profit margin over the pre-bushfire years of FY2016-19—2.48% (see Table 7).

We note that these financial years were particularly lucrative relative to the hardwood division's historical mediocre performance. Again, choosing these especially profitable years was consistent with our overall philosophy of allocating FCNSW with the most favourable assumptions possible.

Input	Value
Discount rate	7%
Forgone revenue if logging halts in the North East RFA	$69,470,000/year
Average operational margin between FY2016-19	2.48%
Avoided costs from logging	$67,750,000/year

Table 7 Status quo inputs for native logging in the North East RFA
Source Blueprint Institute Analysis

Carbon

Our valuation of carbon abatement as a result of ceased native timber logging in the North East RFA region was based on a 2016 FWPA study. The study looked at the North Coast and used life cycle assessments to predict carbon abatement, including the influence of carbon leakage.

Based on the average change in carbon abatement relative to business as usual over the long-term (65 years), derived from the aforementioned study, ending logging, and preserving the native forests in the region for conservation purposes would abate 0.45 million tonnes of carbon annually. Over a 17-year timeframe, this equates to a valuation of $174 million (based on the March 2023 Australian carbon credit unit spot price of $36.65 per tonne, and a seven percent discount rate).

Valuation of this amount of carbon sequestration is unavoidably imprecise. There is no one uniform carbon price in Australia, and the trajectory of prices is subject to market fluctuations and unpredictability. During the Emissions Reduction Fund most recent auction in April 2022, the average price per tonne of contracted carbon abatement was $17.35. By contrast, Australian Carbon Credit Units were auctioned at a spot, or marginal, price of $36.65 in March 2023.

Carbon prices	Values
Australian Carbon Credit Unit marginal price	$36.65
Emissions Reduction Fund average price	$17.35

Table 8 Difference in domestic carbon price (March 2023)
Source Australian Carbon Credit Unit, Emissions Reduction Fund, Blueprint Institute Analysis

Tourism

Construction projects include the building of park boundaries, multi-day walks, and core infrastructure. Estimates for each of these line items are detailed below.

Variables	Value	Units
Area	100,000	hectares
Park infrastructure	12	$/hectare
Trail	50	kilometres
Trail cost	200	$/metre
Maintenance	5	$/metre
Boundary	900	kilometres
Boundary fencing	5,000	$/kilometres
Construction timeline	5	years
Park worker average wage	80,000	$/year
Park workers required	25	workers
Visitors in Year 1	30	% of total visitors
Visitors in Year 2	40	% of total visitors
Visitors in Year 3	60	% of total visitors
Visitors in Year 4	80	% of total visitors
Visitors in Year 5+	100	% of total visitors
Visitors	86,269	visitor nights
Visitor spend	210	$/visitor night
Discount rate	7%	
Years	17	

Table 9 Tourism modelling inputs
Source Blueprint Institute analysis

The establishment of a 50-kilometre trail would cost $10 million assuming an estimated cost of $200 per metre—based on the construction of the Grampians peak trail which cost an average of $192 per metre.

Core park infrastructure such as tracks, signage, interpretation signs, picnic sites, and campsites are vital to attract increased tourism. We have inferred a cost of $12 per hectare based on a relevant case study. Therefore, assuming an area of 100,000 hectares, (just under a third of the harvestable area of native forests in the North East region) a $1.2 million initial investment would be needed in the construction of core park infrastructure.

A cost of $5,000 per kilometre was used to estimate the expenditure involved in the construction of a boundary fence. This figure was derived from examples of previous park establishments. Assuming a boundary of 900 kilometres, the cost would be $4.5 million. The estimated cumulative initial cost for setup is $15.7 million.

We assume a five-year timeframe for construction—consistent with previous, comparable modelling.

We have estimated that a park of this size would require approximately 25 full-time workers based on previous case studies. We have also included a cost of $5 per metre to maintain the 50km walking trail. Thus, total ongoing costs relating to both park maintenance and staffing will be $2.25 million annually.

Average visitor numbers to National Parks and Wildlife services within northern New South Wales were extrapolated from a recent Roy Morgan report. The same report indicated that on average, 4-6% of park visitors stay overnight. Thus, taking the visitor numbers from 2018, we estimated that a national park in the North East of New South Wales could attract 86,269 visitor nights. Data obtained from Destination New South Wales was used to ascertain the average spend per night by visitors to the North Coast.

Industry adjustment package

	Inputs	Payment per unit	Total
Redundancy and retraining — North Coast	500[1] workers	$120,000 per worker	$60,000,000
Harvester and hauler redundancy and business transition voucher	39 firms	$275,000 per firm	$10,725,000
Mill plant and equipment redundancy	151 aggregated in both north and south coast	$275,000 per firm	$37,750,000
Wood Supply Agreement buyout	2,045,000m^3	$19 per cubic metre	$38,855,000
Regional economic diversification			$64,000,000
Grand Total			**$215,105,000**

Table 10 Industry adjustment inputs
Source Blueprint Institute analysis

Our industry adjustment package was designed to be broadly similar to those already implemented in Victoria and Western Australia. However, we made a series of deliberate choices in order to produce an overestimate of total costs to compensate for the limited number of inputs we modelled. This was to account for additional costs, like those for mental health and wellbeing support, that will be incurred but are difficult to estimate in advance.

Specifically, we allocated the maximum amount of $120,000—available only to the most senior of employees in Victoria—to all 500 long-term direct jobs available in harvesting, haulage, and sawmills in the North Coast region. Similarly, as we could not find geographically disaggregated data, we allocated $275,000—as in Victoria, $250,000 in plant and equipment redundancy payments and $25,000 in business transition support—to all 151 mill plants along both the North and South Coast. We also allocated $275,000 per firm to all 39 harvest and haulage firms on the North Coast.

Wood Supply Agreements with sawmills and other timber processors along the North Coast were all recently extended until 2028. These are legal contracts between FCNSW and the sawmills and will have to be bought out.

We based our estimate of the cost of the buyouts on precedent—specifically, FCNSW reached a deal with Boral (a sawmill operator) to buy back a total of 450,000m3 of high-quality sawlog allocation in exchange for $8.55 million, or $19 per cubic metre. Given our projection of an annual yield of 409,091m3, we calculate that, through 2028, a total of 2,045,000m3 of allocation will have to be bought out. This results in a total cost of about $39 million.

Finally, as in Victoria, we allocated $64 million for a broad community support fund, including $36 million "to grow businesses and create jobs in affected communities," $22 million for local development plans, and $5.5 million for economic diversification planning to "support affected local economies' transition to new and sustainable industries."

We assumed all these funds would be paid out immediately, and thus, with respect to our net-present value calculations, no discounting took place.

[1] Based on the Natural Resource Commission's long-term post-bushfire job availability projection

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Shifting baselines clarify the impact of contemporary logging on forest-dependent threatened species

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Abstract

Despite the importance of protecting forests and woodlands to achieve global climate and biodiversity goals, logging impacts persist worldwide. Forestry advocates often downplay these impacts but rarely consider the cumulative threat deforestation and degradation has had, and continues to have, on biodiversity. Using New South Wales (Australia) as a case study, we quantify the extent of deforestation and degradation from 1788 (pre-European colonization) to 2021. We used historical loss as a baseline to evaluate recent logging (2000–2022) and the condition of the remaining native forest and woodland. Condition was quantified by measuring the similarity of a current ecosystem to a historical reference state with high ecological integrity. Using these data, we measured the impacts on 269 threatened terrestrial species. We show that possibly over half (29 million ha) of pre-1788 native forest and woodland vegetation in NSW has been lost. Of the remaining 25 million ha, 9 million ha is estimated to be degraded. We found recent logging potentially impacted 150 species that had already been affected by this historical deforestation and degradation, but the impacts varied across species. Forty-three species that were identified as impacted by historical deforestation and degradation and continue to be impacted by logging, now have ≤50% of their pre-1788 extent remaining that is intact and nine species now have ≤30%. Our research contextualizes the impact of current logging against historical deforestation and highlights deficiencies in environmental assessments that ignore historical baselines. Future land management must consider both the extent and condition of remaining habitat based on pre-1788 extents.

KEYWORDS

conservation assessment, deforestation, degradation, environmental policy, extinction, impact assessments, species endangerment

1 | INTRODUCTION

The global native forest and woodland estate harbors up to 100 million different species (80% of all terrestrial plants and animals (United Nations, 2021)), sequesters a net 7.6 billion metric tonnes of CO_2 per year (1.5 times more carbon than the United States emits annually (Harris et al., 2021)), and provides essential ecosystem services that directly support more than 1.6 billion people (IUCN, 2021; UNEP and FOA, 2020). Despite their critical role in helping humanity overcome the challenges of biodiversity loss, climate change, and achieving global sustainability (FAO and UNEP, 2020), forests and woodlands are among the most structurally altered terrestrial biomes on Earth (Williams et al., 2020).

Deforestation is defined as the outright removal and permanent conversion of forest or woodland to a non-woody land use, whereas degradation is defined as the gradual process of function or biomass decline, changes to taxa composition, or erosion of soil quality (European Union Reducing Emissions from Deforestation and forest Degradation, 2022). Both deforestation and degradation are urgent environmental problems, driving considerable global protection agendas (e.g., Leaders pledge for Nature, 2022; Secretariat of the Convention on Biological Diversity, 2022) and restoration goals (The Bonn Challenge, 2020; Trillion Trees, 2021). Deforestation and degradation rates are increasingly well documented at both global (Beyer et al., 2019; Grantham et al. 2020a; Williams et al., 2020) and national scales (Grantham et al. 2020b; Williams et al. 2021a). However, the cumulative impact of deforestation and degradation on forest-dependent species' habitat, over the long timescales humans have been impacting forests through industrial land uses, is often ignored in contemporary environmental impact assessments.

Thus, a major knowledge gap is a holistic, contextual assessment of contemporary drivers of degradation against a historical quantification of deforestation and degradation. In Australia, there have been published studies examining the extent of deforestation and fragmentation of forests between pre-European colonization (1788) and 2009 (Bradshaw, 2012) and the extent of recent deforestation of forest-dependent threatened species habitat (Ward et al., 2019). However, no assessment of the ongoing impact of native forest and woodland logging, a manageable and contemporary driver of degradation, has been considered in the holistic context of historical impacts.

The failure to place logging within a historical conservation context means current environmental assessments and environmental accounting are perpetuating shifting baselines, making them problematic for decisions about future management (Lindenmayer & Laurance, 2012; Papworth et al., 2009; Soga & Gaston, 2018). It also impedes accurate reporting on how much habitat has been destroyed or degraded (Ward et al. 2022a). These contextual impact assessments are crucial to establish how feasible it will be for nations like Australia to meet the goals agreed upon in international agreements such as the Sustainable Development Goals (United Nations Sustainable Development Goals, 2015), the Kunming-Montreal Global Biodiversity Framework (Secretariat of the Convention on Biological Diversity, 2022), and Leaders pledge for Nature, (2022). At local management scales, it will also allow for more complete assessments when analyzing the likely consequences of current and future contemporary degradation through activities like logging. When these activities are undertaken in isolation and not considered in long-term land management histories, relatively small areas that are logged (or planned to be logged) can be presented as inconsequential. This is especially true when small areas are presented as total historical habitats, without also acknowledging how much of that former area is already destroyed or degraded (Rittenhouse et al., 2010).

Here, using New South Wales (NSW), Australia as a case study, we provide an assessment of historical forest and woodland deforestation since 1788 (pre-European colonization of Australia)—2021 alongside an assessment of degradation (from 1788 to 2018). We then assess the impacts of logging (2000–2022), one of several ongoing contemporary drivers of degradation, against historical deforestation, and degradation. This helps to provide an overall assessment of how ongoing drivers are affecting vegetation types and threatened terrestrial (and semi-terrestrial) forest-dependent species.

Australia has many endemic flora and fauna and is one of 17 mega-biodiverse countries. Many of these endemic species have suffered significant declines in recent decades. Australia has 2003 species listed as threatened with extinction by the Federal Government and 103 taxa listed as extinct (Commonwealth of Australia 2022a). Deforestation and degradation is a major cause of biodiversity loss (Fischer & Lindenmayer, 2007; Ford, 2011; Kearney et al., 2023; Mac Nally et al., 2009; Ward et al., 2021). Although we cannot change historical deforestation and degradation beyond focussing on targeted restoration where possible (Mappin et al., 2021; Ward et al. 2022b), key stakeholders and decision-makers can prevent further degradation from logging, especially in areas that are critical for securing threatened species (Ward, et al., 2022). We argue that assessments like the ones undertaken here should be used for future land management decisions, especially when considering the impact of any planned activity that degrades or destroys intact vegetation.

2 | METHODS

2.1 | Study region

Our study covers the state of NSW, Australia, which is proportionally, the second most forested and woody state on the Australian continent. NSW supports more than 1600 plant community types (NSW Government, 2022) and 532 threatened species (233 of which are endemic to NSW) listed as vulnerable, endangered, or critically endangered under the Environment Protection and Biodiversity Conservation (EPBC) Act 1999, Australia's key federal piece of environmental legislation (Commonwealth of Australia, 1999).

2.2 | Threatened species data

To examine the potential impact on threatened species (as of 2022), we first created a list of nationally listed threatened species using the information available from the Federal Government's dataset (Commonwealth of Australia 2022a). The distributions of each of these taxa were then sourced from a publicly available database provided by the Federal Government's Department of Climate Change, Energy, the Environment and Water (retrieved 15th October 2022) using a combination of occurrence records and MaxEnt.

MaxEnt (or maximum entropy modeling) predicts species occurrences by considering the limits of environmental variables of known locations (Elith et al., 2011). The information used to create the MaxEnt modeled distributions of threatened species was sourced from a range of government, industry, and nongovernment organizations with expert opinion and reference to published information. As of 15th October, 2022, there were 532 threatened species, subspecies, and populations (hereafter referred to as "taxa") occurring in NSW (with at least 1% of total distribution), with most distributions generalized to $\sim$1km^2 or $\sim$10 km^2 grid cells (Commonwealth of Australia, 2022a, 2022b). We refined these spatial data to 484 forest-dependent terrestrial or peri-terrestrial species. Forest-dependent is defined as a taxon's habitat that intersects with ≥5% of forest or woodland vegetation groups mapped in the pre-1788 National Vegetation Information System (NVIS 6.0; Commonwealth of Australia, 2020). We further refined this forest-dependent species list using data from Taylor & Lindenmayer, 2023, and expert verification, which resulted in 269 taxa (Taylor & Lindenmayer, 2023). Peri-terrestrial taxa included threatened frogs and turtles. We did not include aquatic or some peri-terrestrial species such as fish or crayfish as the impacts (and method to measure impact) can be markedly different relative to terrestrial systems. We use threatened taxa as the focus of this study, recognizing that historical deforestation and degradation impacts have most likely contributed to their contemporary threatened status.

2.3 | Historical clearing map

We identified the extent of deforestation from 1788 to 2021 using five lines of evidence (Figure 1). The first was the Australian Government's NVIS 6.0 (Commonwealth of Australia, 2020). From the NVIS, we use two spatial layers that summarizes Australia's present ($\sim$2018) and historical extent of native vegetation ($\sim$1788), classified into 32 Major Vegetation Groups determined by structural and floristic information including dominant genus, growth form, height, and cover, as well as one land cover group called "cleared, nonnative vegetation, buildings." The NVIS (1 ha resolution) current and historical

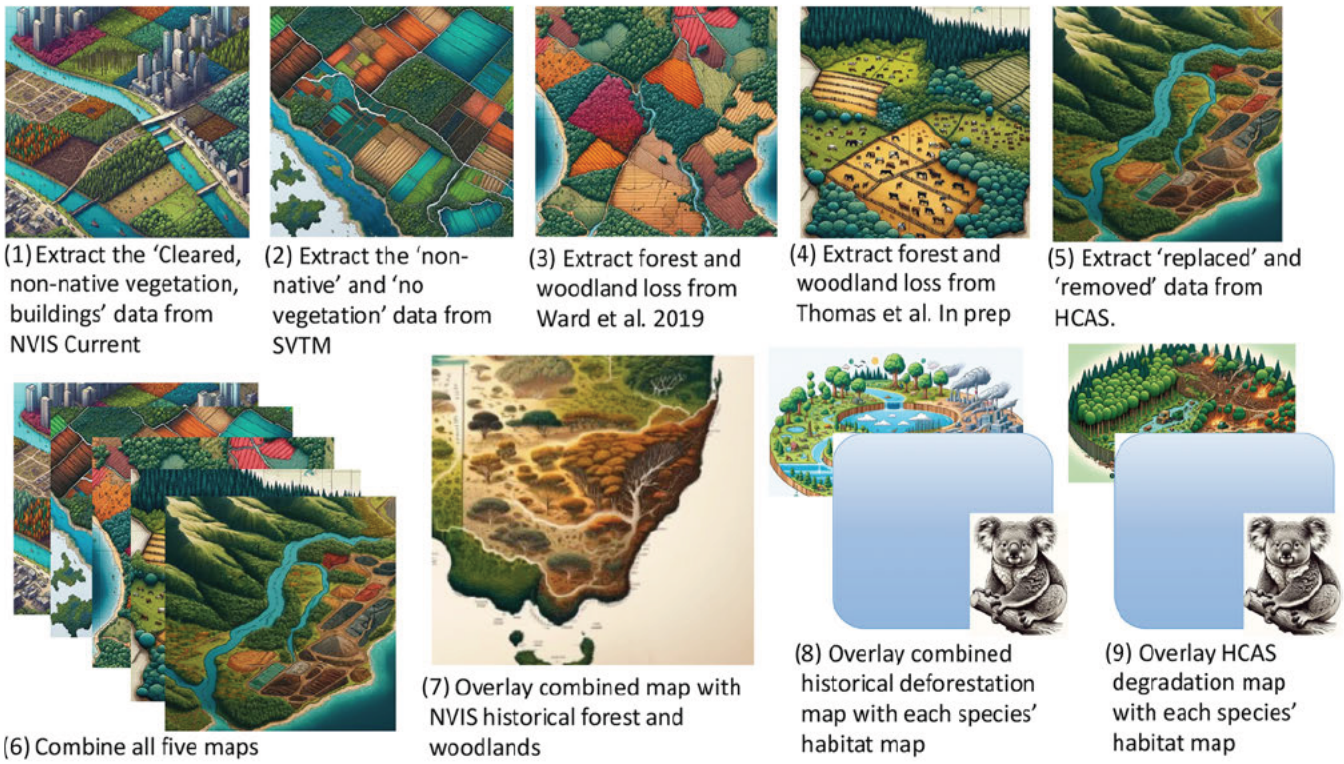

FIGURE 1 The nine steps undertaken in this analysis to create the historical deforestation map (images created by DALL E 2).

vegetation maps are produced by the Australian Government using a rigorous and standardized mapping methodology, and are explicitly designed for comparative purposes (Commonwealth of Australia, 2020). The maps are based on vegetation data spanning over 100 individual projects (e.g., field surveys) produced over the last 50 years (Commonwealth of Australia, 2020). While both current and historical maps are indicative, we propose that comparing these two maps is appropriate for approximating changes in vegetation coverage between 1788 and now, especially with the inclusion of the category identified as "cleared, nonnative vegetation, and buildings" in the current layer of NVIS (Simmonds et al., 2019). The "cleared, nonnative vegetation, and buildings" category corresponds to areas with all or most native vegetation removed, and is now urban areas and cropland. It also includes a wide range of grazing land where the native trees and shrubs have been removed, as well as areas where the understorey is dominated by introduced species. All areas identified as "cleared, nonnative vegetation, buildings" in the current NVIS were extracted from the state-wide native vegetation groups and made the primary subject of the analysis (i.e., all other areas are dropped).

The second map used to identify forest and woodland loss was the state vegetation type map (SVTM), which is a state-wide vegetation map using a vegetation classification hierarchy, including vegetation formations, vegetation classes, and plant community types (NSW Government, 2022). As well as vegetation groups, such as grassy woodlands, semi-arid woodlands, and freshwater wetlands, the SVTM also identifies "nonnative" and "no vegetation" as of 2021. The SVTM is more current compared to the NVIS 2018 because it is based on the best available aerial and satellite imagery (i.e., SPOT 5, SRTM, Landsat), a collection of environmental variables, and existing vegetation mapping using 93,227 vegetation plots up until 2021 (NSW Government, 2022).

We used two additional forest and woodland loss spatial maps (Ward et al., 2019; Thomas et al., 2024)—derived from Australia's National Carbon Accounting System (NCAS) forest and woodland cover dataset—to identify forest and woodland clearing from 2000 to 2021. The NCAS pixels depict forest and woodland coverage into three categories: "2" represents forests, "1" indicates sparse woodlands, and "0" signifies areas without forest or woodland vegetation. Ward et al. (2019) and Thomas et al. (2024) determined habitat loss for a specific year by comparing the average pixel value of the preceding 10 years with the average value for the subsequent 2 years. A minimum difference of one in these values indicated habitat loss. This methodology was adopted to distinguish permanent environmental changes from short-term natural fluctuations. Consequently, we produced binary maps illustrating the loss of forest and woodland over 19 distinct periods, starting from 2000 to 2002, followed by 2002–2004, and then annually up to 2021. These 19 maps were then merged together using ArcGIS Pro version 3.1.0 (ESRI, 2023).

The fifth map utilized was the habitat condition assessment system (HCAS) version 2.1 applicable to 2018 (Harwood et al., 2021; Williams et al. 2021a). HCAS is a way of combining environmental data, remote sensing data, and intact condition reference sites to provide a consistent estimate of habitat "condition" or quality for all locations across Australia (Harwood et al., 2016). Condition is defined as the predicted capacity to support the wildlife expected in a given area under natural conditions (Williams, Tom, et al., 2021). HCAS v2.1 provides, for every 250m^2 pixel, a score from 0 to 1, which can be broken up into five ordinal categories including residual (0.81–1), modified (0.61–0.80), transformed (0.41–0.60), replaced (0.21–0.40), and removed (0.20–0), to approximate the generalized states and transitions narrative proposed by Thackway and Lesslie (2008) for Australian native vegetation, and as used in National State of the Environment reporting (Thackway & Lesslie, 2008; Williams et al. 2021b).

To create a deforestation map from 1788 to 2021, we used a Boolean logic to identify if a given location was identified as lost in any of the five maps (i.e., the current NVIS "cleared, nonnative vegetation, and buildings" data, SVTM "nonnative" and "no vegetation" data, the two forest and woodland loss datasets from Ward et al. (2019) and Thomas et al. (2024), and HCAS "replaced" and "removed" data). To identify just deforestation of forests and woodlands, we overlayed this combined map with forest and woodland vegetation groups as per the historical NVIS map (from hereon, referred to the historical deforestation map).

We overlayed the historical forest and woodland clearing map with individual taxa distribution maps to quantify impact for the 269 EPBC Act listed forest-dependent taxa within NSW. To quantify how much of the remaining taxa distribution was degraded, we overlayed the modified (0.61–0.80) and transformed (0.41–0.60) pixels from the HCAS map (hereon referred to as the "degradation map") with individual taxa distribution maps. We acknowledge that in some cases, calculations of loss and degradation for specific taxa may be an underestimate, as we used only distributions for where species occur currently, which may not be their full historical distribution. For most taxa, their pre-European colonization distributions are unknown as vegetation was destroyed or degraded before documentation by Western science. Where historical distributions are larger than the current estimates, our analysis will underestimate the extent of historical impacts of deforestation and degradation. When reporting on species impacts, we considered only the forest or woodland portion of habitat that was within NSW.

2.4 | NSW logging data

Logging data were retrieved from Forestry Corporation of New South Wales (FCNSW) Open Data Site (FCNSW, 2021) (retrieved November 17, 2022). These data show forests and woodlands that have been logged between 2000 and August 2022. We removed all plantations (provided by FCNSW in August 2021) from the logging layer because plantations were captured in the above deforestation layer. To ensure no double counting of deforestation or degradation, we subtracted any logging overlaps from the historical deforestation layer and the historical degradation layer. We removed any areas that were logged prior to 2000, which is the year the EPBC Act was inaugurated. We intersected taxa distributions to the boundaries of completed logging areas to estimate the overall extent of degradation impacts by logging. To assess the condition of remaining forest and woodland within taxa distributions (i.e., not deforested, degraded, or logged), we intersected all taxa distributions with the residual (0.81–1), modified (0.61–0.80), and transformed (0.41–0.60) pixels in HCAS. Here on, we refer to residual as "intact", and modified and transformed is described as "degraded."

Under the EPBC Act, a taxon may be listed as critically endangered, endangered, or vulnerable for many reasons, including if it experiences a population size reduction of >80%, >50%, or >30%, respectively, measured over the longer of 10 years or 3 generations (where threats are ongoing and unresolved). A decline in area of occupancy, extent of occurrence, and/or quality of habitat exceeding these thresholds can be taken as an indicator of equivalent population declines. Here, we assessed the combination of historical deforestation and degradation, contemporary logging, and remaining condition of forest and woodland within taxa distributions against such criteria.

3 | RESULTS

By 2021, the total forest and woodland remaining in NSW was ~25 million ha. The amount of forest and woodland destroyed due to deforestation was ~29 million ha (amounting to 54% of the 1788 native forest estate, which was originally 55 million ha) (Figure 2). Most deforestation has been concentrated along the east coast of NSW,

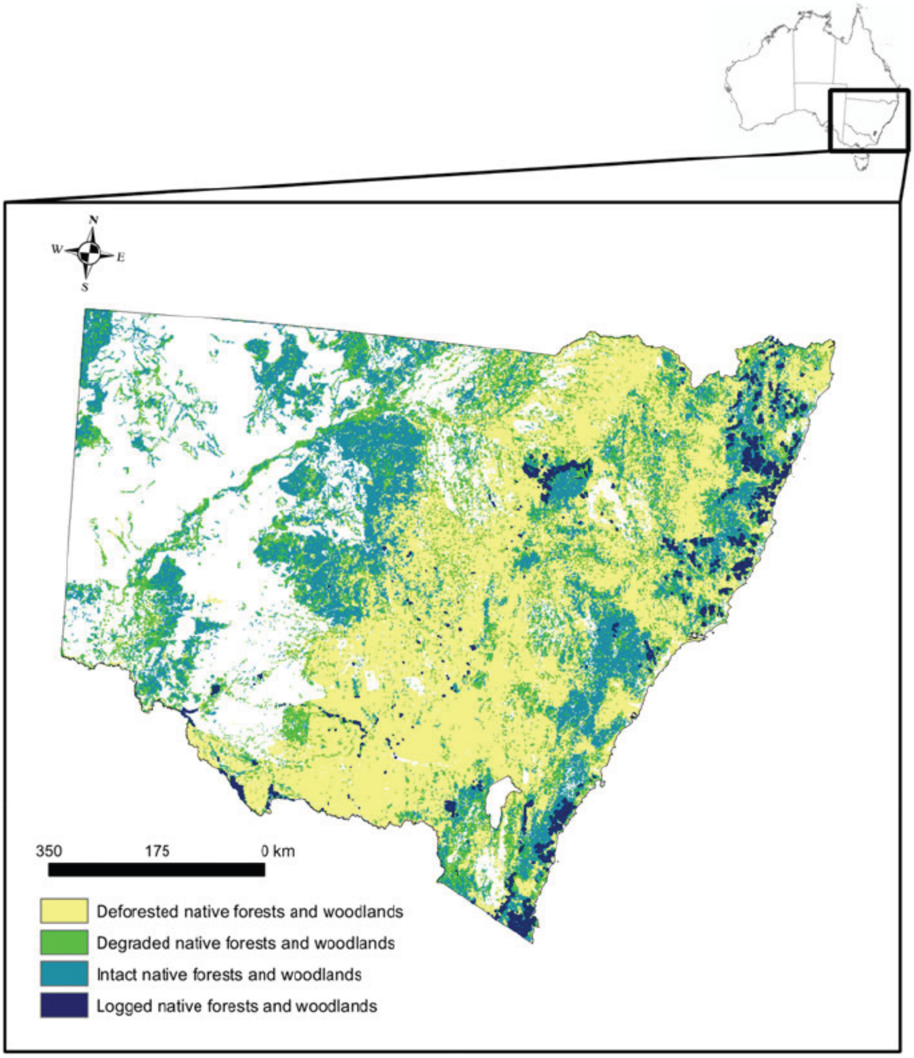

FIGURE 2 Map of 2000 2022 logged areas in NSW represented in dark blue with dark blue border for increased visibility at this scale. From 1788 to 2021, cleared forests and woodlands is represented in yellow, whereas remaining degraded native forests and woodlands is represented in green. Remaining intact native forests and woodlands is represented as teal.

within several major vegetation groups including Eucalypt Woodlands (10 million ha [35%] remaining), Eucalypt Open Forests (5 million ha [48%] remaining), and Eucalypt Open Woodlands (1 million ha [35%] remaining), based on the historical NVIS mapping product.

Of the remaining forests and woodlands, approximately 16 million ha (30% of all pre-European forest and woodland) is intact, and 9 million ha is degraded. Some vegetation groups have been heavily degraded even if they have not been extensively cleared. When assessing the condition of remaining forest and woodland vegetation groups, 72% of remaining Casuarina forests and woodlands is degraded, 45% of remaining Melaleuca forests and woodlands is degraded, and 39% of remaining Eucalypt open woodland is degraded.

We found that contemporary degradation in the form of logging continues in 12 of 15 of the major forest and woodland vegetation groups in NSW. Our analysis found the area of logged forests constitutes mostly Eucalypt tall open forests (150,000 ha) and Eucalypt open forests (135,000 ha). The total extent of logging within NSW from January 2000 to August 2022 was estimated at 435,000 ha.

3.1 | Potential impact of deforestation on threatened taxa

All 29 million ha of historical deforestation overlapped with the distributions of at least one of the 269 threatened taxa considered in this study. In total, 259 (96% of taxa assessed) threatened taxa have potentially been impacted (≥1% of NSW distribution) by historical deforestation. The extent of overlap between deforestation and species distributions ranged from 1% to 99% (mean = 40%, median = 36%). Flora that have the lowest proportional distribution remaining include *Eucalyptus alligatrix* subsp. *miscella* (4% of woody distribution remaining), spiked rice-flower (*Pimelea spicata*; 9% of woody distribution remaining), and Coastal Fontainea (*Fontainea*

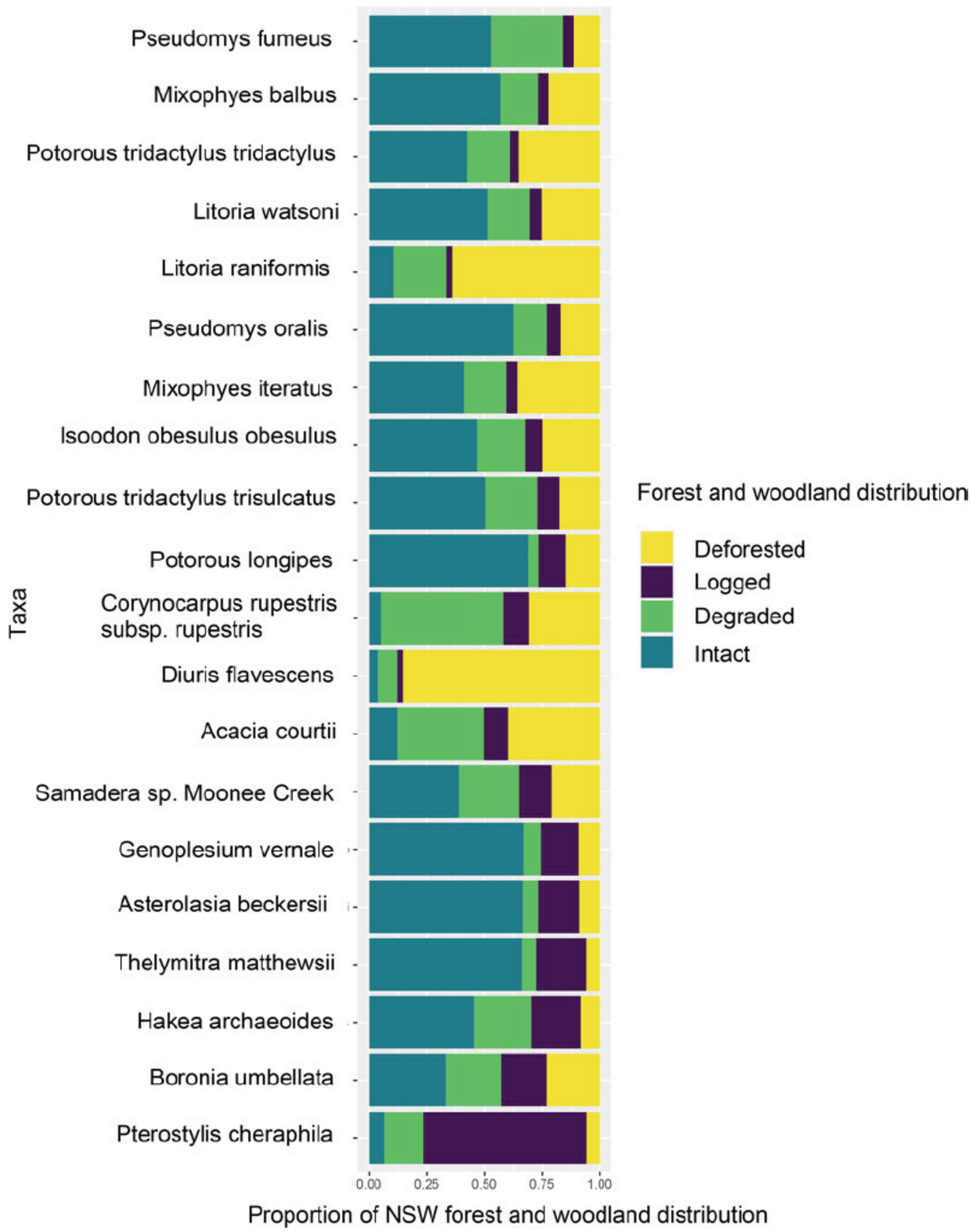

FIGURE 3 Proportional spatial overlap of historical deforestation (purple), logging (blue), remaining degraded (green), and remaining intact (yellow) highlighting the top 10 flora and top 10 fauna likely impacted by logging. The list shows species, starting from the one most affected by logging (bottom) to the least affected (top), based on the areas that are still intact, degraded, or logged.

oraria; 10% of woody distribution remaining). All three species occur only in NSW. Fauna that have potentially the lowest proportional distribution remaining include Sloane's froglet (*Crinia sloanei*; 3% of woody distribution remaining in NSW), Key's matchstick grasshopper (*Keyacris scurra*; 13% of woody distribution remaining in NSW), and golden sun moth (*Synemon plana*; 14% of woody distribution remaining in NSW).

3.2 | Potential impact of logging on threatened taxa

Our results, based on the spatial resolution of the data, show that all areas logged between 2000 and 2022 overlapped with the modeled distributions of at least one threatened taxa and, in total, 150 taxa (56% of species assessed) were potentially impacted by logging

(Appendix S1). Of these 150 taxa, 13 are listed as Critically Endangered, 51 as endangered, and 86 as vulnerable. The flora with the highest proportion of NSW forest and woodland distribution overlapped with logging includes Floodplain rustyhood (*Pterostylis cheraphila*) (75% of remaining woody distribution overlapped with logging), Orara boronia (*Boronia umbellata*; 26% of remaining woody distribution overlapped with logging), and *Hakea archaeoides* (24% of remaining woody distribution overlapped with logging; Figure 3). Fauna with the highest proportion of NSW distribution that overlapped with logging include long-footed potoroo (*Potorous longipes*, 14% of remaining woody distribution overlapped with logging), southern mainland long-nosed potoroo (*Potorous tridactylus trisulcatus*, 12% of remaining woody distribution overlapped with logging) and southern brown bandicoot (*Isoodon obesulus obesulus*, 9% of remaining woody distribution overlapped with logging; Data S1).

Taxa with the most distribution by area that overlapped with logging included koala (*Phascolarctos cinereus*, 400,000 ha), south-eastern glossy black-cockatoo (*Calyptorhynchus lathami lathami*, 370,000 ha), and spot-tailed quoll (*Dasyurus maculatus maculatus* [SE mainland population], 310,000 ha). Across all species potentially impacted by logging, the size of the distributions in NSW varied dramatically with species such as Julian's hibbertia (*Hibbertia spanantha*) having as little as 206 ha (min), painted honeyeater (*Grantiella picta*) having 51 million ha (max), with 90,477 ha the median and 1.6 million ha the mean. The large distributions of some species such as koala have a total NSW distribution of 34 million ha, which may help explain the high overlap with logging (395,000 ha). Other species such as *H. archaeoides* have a total NSW distribution of 6000 ha, yet had ~24% of remaining woody distribution that overlapped with logging.

3.3 | Potential impact of degradation on threatened taxa

We assessed the condition of the remaining forest and woodland distribution after historical deforestation and degradation, and contemporary logging against EPBC Act listing criteria (see methods) and found that two taxa have ≤10% intact forest and woodland distributions remaining. These were the Endangered Sloane's froglet, of which 5% of remaining forest and woodland distribution is predicted to be intact and the vulnerable Glenugie karaka (*Corynocarpus rupestris* subsp. *rupestris*), of which 9% of remaining forest and woodland distribution is predicted to be intact. Under the EPBC Act criteria, these two species may be eligible for critically endangered status. The distributions of these species possibly continues to be impacted by logging. Forty-one taxa have between 20% and ≤50% of remaining forest and woodland habitat intact (two are critically endangered, 14 are endangered, and 25 are vulnerable; Figure 4a,b). We found 59 taxa have between 50% and ≤70% of remaining forest and woodland habitat intact (six are critically endangered, 16 are endangered, and 36 are vulnerable). When we considered all taxa (rather than just those impacted by both logging and historical deforestation and degradation), we found that two taxa (*E. alligatrix* subsp. *Miscella* and *F. oraria*) could have little to none intact forest and woodland distributions remaining, 19 taxa have ≤20%, 80 taxa have ≤50%, and 85 taxa have ≤70% (noting these species still have degraded habitat which they currently persist within).

4 | DISCUSSION

The area of native forest and woodland in NSW deforested between 1788 and 2021 was ~29 million ha. This equated to 54% of all native forests and woodlands across the state or an area approximately the size of New Zealand. This extensive deforestation potentially reduced the distributions of many native species, including 269 forest-dependent threatened taxa we assessed here. Despite these large historical impacts, the potential habitat of 150 of these threatened taxa continues to be logged. We found that 43 threatened species that were found to be potentially impacted by historical deforestation and degradation and continue to be impacted by contemporary logging, now have ≤50% of their precolonization extent remaining that is in intact woody vegetation. Two of these species (Sloane's froglet and pale yellow doubletail *Diuris flavescens*) have approximately <12% of their NSW forest and woodland distribution remaining.

Although deforestation has clear and immediate impacts on biodiversity such as removing habitat, resources, food, and shelter, forest degradation is more subtle and often overlooked (Thorn et al., 2020). Degradation, driven by activities such as logging, is the gradual process of forest biomass decline, changes to taxa composition, or erosion of soil quality (European Union Reducing Emissions from Deforestation and forest Degradation, 2022). Native forest logging has severe degrading impacts on forests and subsequent forest-dependent biodiversity, such as reducting critical resources necessary for taxa survival, including food, shelter, and breeding areas (Ashman et al., 2021;

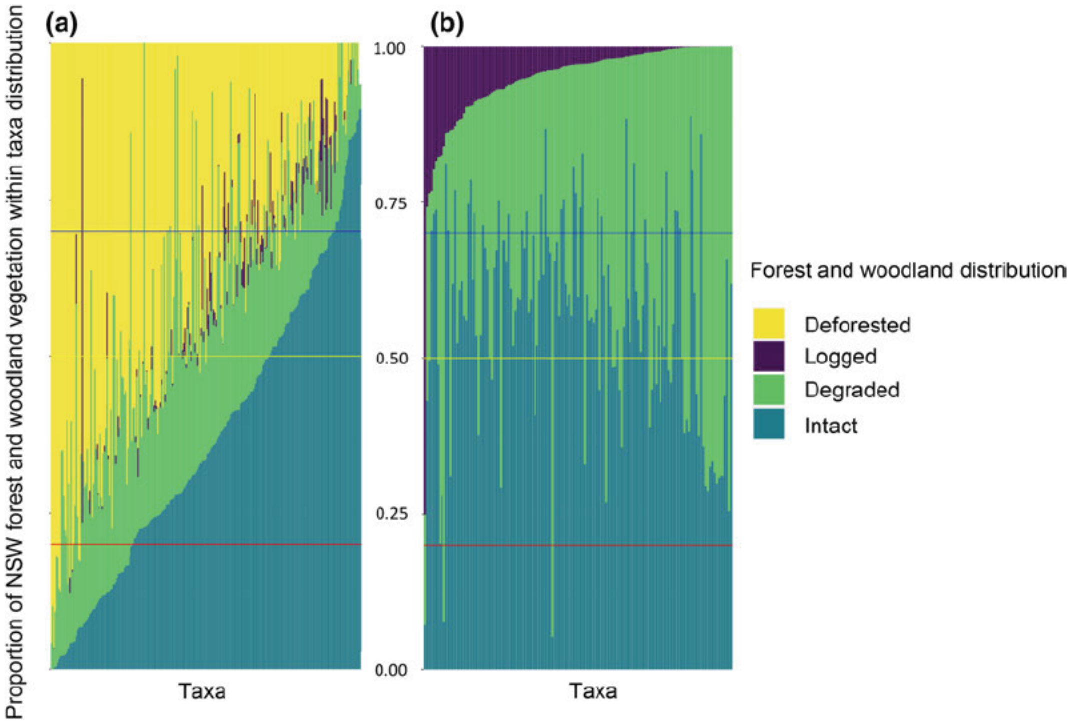

FIGURE 4 (a) Proportion of each taxa's distribution (*x* axis) impacted by both historical deforestation, historical degradation, and contemporary logging. We show the combination of forest and woodland distribution potentially impacted from deforestation (brown) and logging (yellow) and highlight the condition of the remaining forest and woodland vegetation within taxon distributions as either degraded (light purple) or intact (dark purple). (b) A subset of taxa highlighting only those impacted by logging. The proportion of each taxa's distribution (*x* axis) impacted by contemporary logging (yellow) only, highlighting the condition of the remaining forest and woodland vegetation within taxon distributions as either degraded (light purple) or intact (dark purple). The horizontal lines on both figures indicate EPBC Act threat status thresholds of ≤70% (yellow), ≤50% (blue), and ≤ 20% (red) for vulnerable, endangered and critically endangered, respectively. Both figures are ordered based on proportion on forest and woodland distribution remaining that is intact.

Lindenmayer et al., 2013). Another significant impact of logging is the network of roads needed to transport timber out of forests and woodlands and into processing facilities such as sawmills. Road networks cause major problems such as facilitating invasive predator access (e.g., cats (*Felis catus*), dogs (*Canis lupus familiaris*), and foxes (*Vulpes vulpes*)), and the spread of pathogens (e.g., chytrid fungus *Batrachochytrium dendrobatidis* and *Phytophthora cinnamomi*); (Boston, 2016). These drivers of degradation often have larger effects than the reduction of vegetation from constructing the road. Some of these impacts may not manifest for several years or decades after logging, often resulting in an extinction debt (Szabo et al., 2011).

Logging native forests can lead to further degradation as it increases the severity and frequency of wildfires (Lindenmayer et al., 2020; Lindenmayer & Zylstra, 2023; Taylor et al., 2014). Logged areas burned with significantly increased severity during the record 2019/20 fire season in NSW (Lindenmayer et al., 2022). Fire is a critically important ecological disturbance that affects landscape heterogeneity, recruitment, community composition, and ecosystem function (Koltz et al., 2018; McLauchlan et al., 2020). For example, many obligate-seeding plant taxa, which are killed by fire require inter-fire intervals that are long enough to allow recruiting individuals to reach maturity and set seed into the seed-bank to ensure their continued persistence (Enright et al., 2015; Keith, 1996). However, drivers such as anthropogenic climate change and logging are resulting in fire becoming more prevalent, larger in scale, and occurring outside of historical fire seasons (Dowdy et al., 2019; Lindenmayer et al., 2020). This not only causes direct mortality of taxa, removal of habitat, and reduction in resources, fires can also shift ecosystems to different states, or interact with existing threatening process resulting in further degradation (Suding et al., 2004). Such changes in fire regimes represent a key threatening process to more than 800 Australian threatened native species, and 65 threatened communities (DAWE, 2020; Ward et al., 2020). While we cannot control future wildfires, we can implement actions that will help reduce their impact, such as decarbonization and ending native forest logging.

Our results show that is it critical to more holistically assess the impacts of potentially significant and negative actions on threatened species, by placing it in the context of past deforestation and degradation. Under the EPBC Act, proposed destructive actions are individually assessed and do not consider the cumulative impacts (Dales, 2011; Tulloch et al. 2016a) or are not assessed at all with 93% of clearing events not being referred to the EPBC Act (Ward et al., 2019). While relatively limited amounts of impact in any given year may seem insignificant; the combined deforestation and degradation of habitat over 236 years can lead to the extinction of species via many small modifications of habitat (i.e., "death by a thousand cuts") (U.S. Environmental Protection Agency, 1999; Reside et al., 2019; Tulloch et al. 2016b). Ongoing logging perpetuates the problem of shifting baselines (Lindenmayer & Laurance, 2012). The consequences of shifting baselines are significant because it can lead to a gradual decline in environmental standards and goals (Angelstam et al., 1995; Gustafsson et al., 2010). This can result in a failure to take necessary conservation and restoration measures, ultimately leading to a further decline in the health and biodiversity of ecosystems.

Our quantitative results have implications that are useful for evaluating the effectiveness of current policies in NSW. Between 2000 and 2022, NSW logged approximately 435,000 ha of native forest and woodland, all of which overlapped with the distributions of at least one threatened forest-dependent taxon. This impact assessment is likely an underestimate given the rate of new discoveries of species in Australia. For example, in 2022 alone, scientists discovered an additional 139 new species in Australia (CSIRO, 2022). Although the EPBC Act is the primary legislation aimed at protecting biodiversity, the Regional Forest Agreements (RFA) Act 2002 is geared toward ensuring access to forests while ensuring the conservation of forest biodiversity and protection of environmental integrity (The Department of Agriculture, Water and the Environment, 2020). Unfortunately, RFAs have been exempt from following EPBC Act protections (Lindenmayer & Burnett, 2022), even when there are clear breaches, such as degrading threatened taxa habitat which is likely to have a significant impact on those species (Commonwealth of Australia, 1999). Therefore, while logging in NSW has degraded 435,000 ha of native forest across 143 threatened taxa distributions, logging is still legal under current legislation (Ashman & Ward, 2022). Our research suggests that forestry regulations do a relatively poor job at limiting the impacts of logging on the landscape distribution of biodiversity; especially given historical deforestation and degradation, as well as other ongoing forms of contemporary degradation. A broad implication might be that either logging will soon have to stop (to avoid biodiversity impacts) or transform in its approaches to removing far less timber, under much more careful biodiversity spatial planning, while also restoring vast areas where habitat has been lost (using fine-scale spatial analysis to guide that restoration).

Australia has recently committed to international agreements to halt taxa extinctions (e.g., Global Biodiversity Framework; Secretariat of the Convention on Biological Diversity, 2022), prevent further forest degradation (e.g., Glasgow Climate Pact; UNFCCC, 2021), and reverse biodiversity loss (e.g., Natures Pledge; Leaders Pledge for Nature, 2022). The NSW Government has also made commitments to enhance nature conservation including stopping extinctions inside protected areas, stabilizing, or improving the trajectory of all threatened taxa, and removing threatened taxa from the threatened species list (NSW Government, 2021a). Notably, the NSW Government's Koala Strategy has also committed to doubling koala numbers by 2050 (NSW Government, 2021b). Many countries and jurisdictions are now legislating that commodity production (such as beef, cocoa, soy, and timber) must not contribute to deforestation and degradation. For example, the European Union passed new laws in December 2022 to ensure there is now a due diligence process to demonstrate that imported products have not contributed to deforestation or degradation (European Commission, 2022). In addition to driving species to extinction, and possible inaccessibility to markets, logging in its current form is also not economically viable. A recent analysis measured the costs and benefits of logging over a 30-year period to 2051 and found that ending native forest logging in the southern areas of NSW could result in a $61.96 million saving of taxpayer money (Frontier Economics, 2021). Unfortunately, there has been no commitment by the NSW Government to use holistic, landscape scale approaches to change their current practice or end logging in native forests and transition to sustainable plantations (Morgan et al., 2021).

By spatially mapping species habitats at a landscape scale that have been highly impacted by historical deforestation and degradation, our approach provides a pragmatic pathway to achieve policy objectives, demonstrating how conservation efforts can be strategically aligned with national and international commitments (e.g., Sustainable Development Goals or Global Biodiversity Framework). This approach allows for the identification of key areas where management and conservation interventions are most needed and most effective. By integrating the historical deforestation and degradation impacts with current drivers of degradation within a spatial context, the approach promotes a more holistic understanding of the landscape, encouraging contextual assessments to be the basis of all future land management decisions.

4.1 | Caveats and limitations

We recognize that our historical impact analysis of forest and woodland within the distributions of threatened taxa is likely an underestimate as we have used known and likely to occur distributions based on recent records of taxa. This does not include the contractions of the historical distribution of species that have occurred due to habitat loss and other threatening processes like invasive taxa and altered fire regimes (Ward et al. 2022a). There are also many nonthreatened species, such as aquatic and peri-terrestrial species, that have experienced huge historical habitat loss and ongoing contemporary degradation that have not been captured here, but it is known that sedimentation, destruction of riparian zones, and creation of roads are all major threats to aquatic communities. We recognize that we are relying on modeled datasets including NVIS and HCAS to estimate historical deforestation and degradation. As such, quantification of impacts across large spatial scales is imperfect. In addition, the high degree of overlap between species and logging may be an artifact of the spatial resolution of the species data (i.e., 1 km × 1 km). On this basis, our study can inform strategic level decisions, but not inform finer-scale operational planning. Unfortunately, the NSW Forestry Corporation do not report their impacts on threatened taxa, so we were unable to compare our results with existing data collected by industry staff.

5 | CONCLUSION

Despite strong evidence that Australia's biodiversity is suffering major declines (Legge et al., 2023), degradation by multiple sources including logging, deforestation, and degradation continues. Policy makers and the community must recognize and account for the critical values of intact native forests such as high biodiversity, mitigating climate change, services to people (such as clean water provision and air purification), and their capacity to reduce fire severity. Our research showcases a landscape scale approach to measure the historical impacts of deforestation and degradation, as well as contemporary degradation from one driver, logging. We highlight how threatened taxa may be impacted and emphasize the critical importance of considering these long-term impacts in contemporary settings when it comes to forest management in NSW. These holistic, contextual assessments need to be the basis of all future land management decisions.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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NEFA BACKGROUND PAPER

CLEARING OUR RAINFALL AWAY

Dailan Pugh, February 2017

> *This attractive force of the forests on this island is such that a field in an uncovered situation close to them often suffers a lack of rain whereas it rains almost all year long in woods that are situated within gunshot. It is by destroying part of the trees crowning the heights of this island that one has caused most of the streams that watered it to dry up. I attribute to the same lack of foresight the notable diminishing of the streams and rivers in a large part of Europe.*
>
> **Bernardin de Saint Pierre 'Etudes de la Nature' 1784-8,**
> describing the impact of forests on rain and streamflow in Mauritius (Andreassian 2004).

This review was initiated in response to the question "How do forests affect rainfall?". In the process of reviewing the available scientific literature it became apparent that there is now an overwhelming abundance of evidence that deforestation has had a profound impact on regional climates, including in southern and eastern Australia, and a growing effect on global climates. The answer is "profoundly".

Deforestation accounts for as much as a third of total anthropogenic CO^2 emissions since 1850 and thus is one of the principal contributors to global warming through the greenhouse effect. Though deforestation also has direct biogeophysical effects on rainfall, wind and temperature of similar amplitude, that in some cases is being mistakenly attributed to CO^2 emissions, and in others may be masking the full impacts that CO^2 emissions are having. It is the biogeophysical effects of deforestation that are the subject of this review.

Terrestrial climates evolved over hundreds of millions of years as vegetation colonised the land and created conditions more suitable for its own growth, modifying temperatures, conserving moisture and enhancing rainfall as it progressed inland. Human civilisations emerged within the climate created by the vegetation, modifying the vegetation to suit their purposes, sometimes with dire climatic consequences.

It is well known that climate influences vegetation, and while it has long been recognised by some that vegetation influences climate, we are still only beginning to understand the complexity and scale of the mechanisms involved.

At its simplest, the basis for the hydrological cycle is that water is evaporated from the ocean into the atmosphere, the water vapour is carried by winds across the land until it condenses and falls as rainfall, with excess water entering streams and travelling downhill back into the oceans. All the terrestrial water contained in glaciers, lakes and soil could be depleted by global river runoff in just a few years if it was not replenished by atmospheric flows from the ocean. Rainfall is an outcome of rising atmospheric moisture cooling and condensing around particles (mostly organic) in the air to form water droplets which grow by colliding and merging to create larger droplets until gravity takes over and they fall to earth.

Vegetation does not just respond to rainfall, it actively generates its own. It recycles water from the soil back into the atmosphere by transpiration, creates the updrafts that facilitate condensation as the warm air rises and cools, creates pressure gradients that draw moist air in from afar, and, just to be sure, releases the atmospheric particles which are the nuclei around which raindrops form.

Forests have been described as 'biotic pumps' driving regional rainfall because their high rates of transpiration return large volumes of moisture to the atmosphere and suck in moisture laden air from afar.

While most of our rain originates from evaporation of the oceans, it is estimated that 40% of the rain that falls on land comes from evaporation from the land and, most importantly, from transpiration by vegetation. Recycled water vapour becomes increasingly important for inland rainfall.

Having created and attracted the water vapour, the plants then make it rain. Plants emit volatile organic compounds (VOCs), such as plant scents and the blue haze characteristic of eucalypt forests. They play an important role in communication between plants, and messages from plants to animals, and also between plants and moisture-laden air. They oxidise in the air to form the cloud condensation nuclei around which water drops form.

The transpiration of vegetation also results in evaporative cooling whereby the surface heat is transferred to the atmosphere in water vapour. The resultant clouds also help shade and cool the surface.

Pielke (2001) concluded "*In the context of climate, landscape processes are shown to be as much a part of the climate system as are atmospheric processes*".

There is abundant scientific evidence that deforestation and degradation of vegetation causes significant reductions in rainfall by:

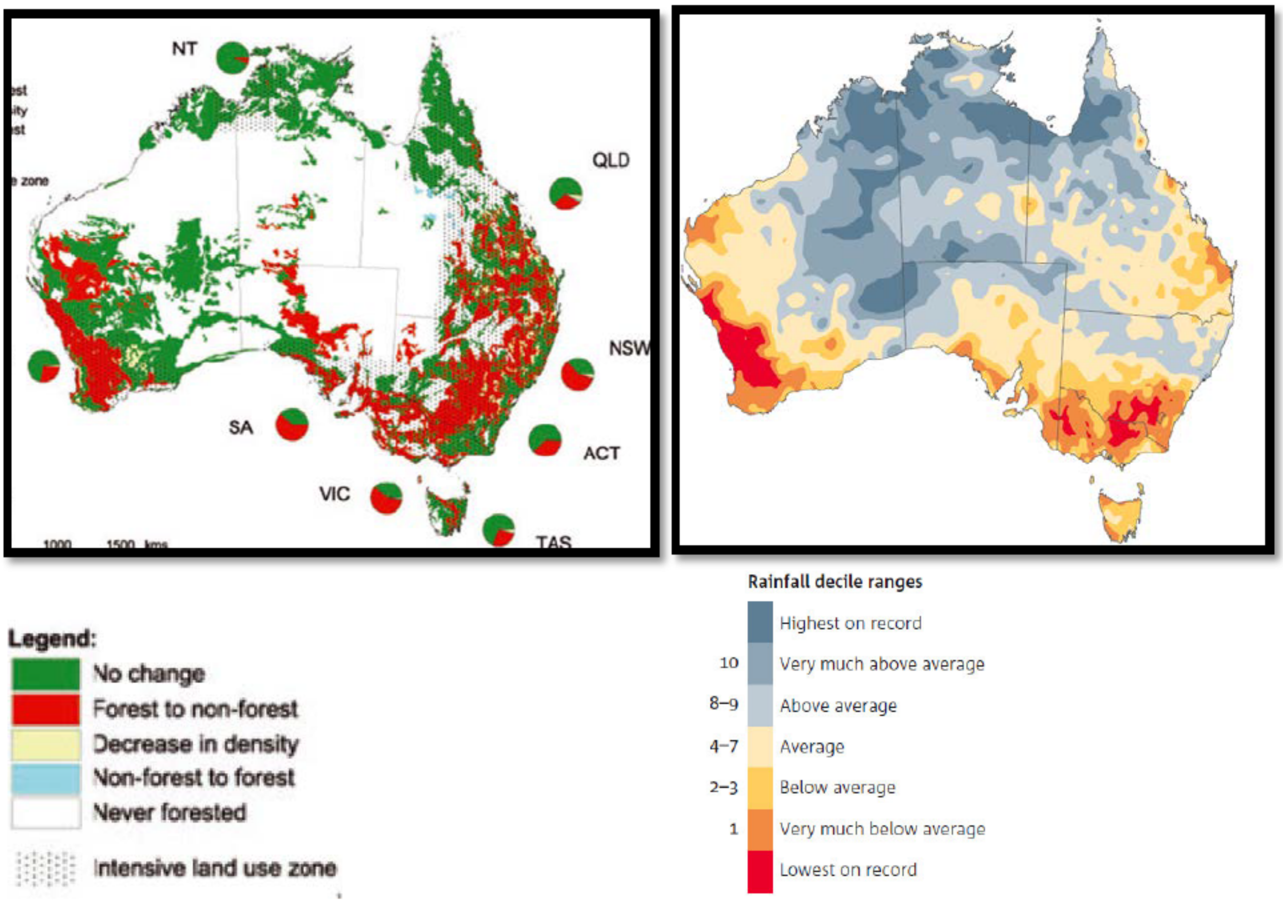
- reducing the recycling of rainfall to the atmosphere by transpiration
- reducing the drawing in of moist coastal air
- reducing updrafts of moist air
- reducing rooting depth and the recycling of deep soil moisture
- increasing loss of water from the land by runoff
- reducing the organic aerosols necessary for the condensation of rain drops.

Deforestation has other climatic impacts; the reduction of surface roughness increases wind speeds, the reduction of transpiration increases temperatures by reducing evaporative cooling and cloud cover, and the burning of vegetation releases soot to the atmosphere where it can reduce rainfall.

There is conjecture that the increased frequency of extensive fires following the arrival of Aboriginal Australians some 50,000 years ago significantly reduced tree cover and thus rainfall in some drier regions, possibly resulting in reduced penetration of monsoon rains into central Australia and increasing aridity.

There is no doubt that the arrival of Europeans just over 200 years ago began the widespread deforestation of most of our most productive lands, and significant degradation of vast tracts of native vegetation by logging and grazing. This has had a profound impact on our rainfall, contributing to significant declines in the most heavily cleared regions in southern and eastern Australia.

It has been estimated that since European settlement, land clearing in eastern Australia has directly resulted in an average summer rainfall decrease of 4-12%, a warming of around 0.4-2°C, and an average 9% increase in surface wind speeds. This conforms with studies from around the world that land clearing significantly affects rainfall and climate.



Comparison between deforestation and rainfall declines: LEFT: The land-cover map of Australia showing changes in native vegetation since European settlement (Source Deo 2011) RIGHT: Rainfall deciles for April-September1997-2013 relative to 1900-2013 (Source: Braganza et. al. (2015).

South-west Western Australia provides a clear example of the folly of over-clearing vegetation. By 1950 30% of the arable area had been cleared, increasing to 72% by 1980. In the mid-1970s a clearing 'tipping-point' appears to have been reached and the region experienced a step-wise change in climate manifesting itself as a rapid 15–20% decrease in rainfall and an associated 50% decrease in runoff into Perth's drinking water catchments. Since 1996 this decline in rainfall from the long-term average has increased to around 25%. In 2001 there was another shift with a further 50% reduction in runoff.

Studies have concluded that in south-west Western Australia up to 50-80% of the rainfall decline since 1970, and 50% of the observed warming since European settlement, could be attributed to land-clearing. Despite the reduction in rainfall, groundwater has risen on cleared lands turning most of the streams saline and affecting over 500,000 hectares of previously productive agricultural land. And while the conversion of oldgrowth forest to regrowth is having the effect of increasing transpiration, it is not compensating for the losses, and with declining rainfalls the water stress is killing trees and drying catchments.

Across drier areas of Australia the removal of deep rooted forests and woodlands has caused watertables to rise, allowing long-buried saline ground-waters to rise towards the surface, with the resultant dryland salinity affecting millions of hectares. This has turned many of our rivers saline, caused widespread degradation of native ecosystems and agricultural lands, destroyed infrastructure, and diminished biodiversity. And it can take decades or centuries for the impacts to manifest. Some 7.5 million hectares of NSW's agricultural lands are considered at risk.

The first section of this review seeks to identify the principal means by which deforestation affects climate, particularly rainfall. In the second section of this review Australia is considered as a case-study of the impacts that deforestation, and the use of native vegetation for hunting, grazing and logging, has had on regional climates.

History is littered with failed civilisations that cleared too much vegetation and changed the climate to one unfavourable for their own survival, such as the Nasca of southern Peru and Anasazi of south-west USA. Clearing and degradation of native vegetation has now progressed to the stage where regional impacts are turning into global impacts. We cannot afford to continue to ignore the climatic consequences that past and ongoing forest clearing and logging are having on Australia, the driest inhabited continent on earth

While recently there has been a focus on the impacts of greenhouse gasses on climate change, it is evident that deforestation plays a significant role in many of the climate changes currently underway, we ignore these impacts at our peril. Pitman *et. al.* (2012) modelled variable changes in rainfall due to deforestation, finding that in regions subjected to significant land-use change "*the impact of landscape change on temperature and some hydrometeorological variables can be similar in magnitude to a doubling of atmospheric* CO^2*", and* that "*land cover change would offset the impact of elevated* CO^2*. Surprisingly, this also included partially offsetting a* CO^2 *induced increase in rainfall over S.E. Asia in three of the four models*".

In relation to the significant effects of Land Use-Land Cover Change (LULCC) de Noblet-Ducoudré *et. al.* (2012) caution:

> *Increased concentration of greenhouse gases in the atmosphere, and the subsequent changes in sea surface temperatures and sea ice extent, are often used as the main drivers of climate change also over land. Our results suggest that such an assumption leads to erroneous conclusions regarding the land surface impacts of climate change in regions where LULCC has been significant. LULCC affects a number of variables to a similar magnitude, but of opposite sign, in increasing greenhouse gas concentrations. LULCC therefore has the potential to mask a regional warming signal, with the resulting risk that detection and attribution studies may miss a clear greenhouse signal or misattribute a greenhouse signal if LULCC is poorly accounted for.*

Current climate changes are primarily consequences of deforestation, injection of massive volumes of aerosol pollutants into the atmosphere and the release of greenhouse gasses such as carbon dioxide. Into the future greenhouse gases will become the increasingly dominant influence, though at this time in our history it is apparent that we can significantly modify the climate changes underway by retaining and restoring our natural vegetation and reducing biomass burning. This will buy us time to redress pollution caused by our use of fossil fuels.

Eiseltová *et. al.* (2012) consider:

> *The water cycle is akin to the 'bloodstream' of the biosphere. Returning water to the landscape and restoring more natural vegetation cover is the only way to restore landscape sustainability. More attention in present-day science needs to be devoted to the study of the role of vegetation in the water cycle and climate amelioration. Restoration of a more natural vegetation cover over the landscape seems to be the only way forward.*

CONTENTS

1. VEGETATION'S ROLE IN GENERATING RAINFALL

Vegetation plays a significant role in climatic processes, from creating microclimates beneath their canopies, to modifying regional winds and temperatures, to enhancing rainfall, and changing atmospheric heat and moisture fluxes at continental scales. There is now abundant evidence that deforestation is having a significant impact on regional climates, and the reasons for this are becoming increasingly apparent.

Far from being passive, vegetation plays an active role in its partnership with climate (Zeng and Neelin 2000). Across the semi-arid Sahel in central Africa, the forests and woodlands of southern Australia, and the mighty Amazon rainforests, clearing, logging and burning of natural vegetation is causing a considerable increase in temperatures, decrease in evapotranspiration and decrease in rainfalls. As observed by Fu (2003):

> *Both the observational and theoretical studies have proved that the destruction of natural vegetation cover, such as destructive lumbering of forests and over cultivation and overgrazing of grassland has been one of the major causes for the deterioration of regional climate and environment.*

At the site level, compared to cleared areas, it is apparent that forests can create their own microclimate, with more stable temperatures (warmer on cold winter nights and cooler on hot days), and with moister soils and higher humidity in dry times (Meher-Homji 1991). Vegetation, and particularly forests, can affect regional climates by:

- transpiring moisture from the ground into the atmosphere to form clouds and generate rainfall
- providing a large area of leaves and other surfaces for evaporation of moisture back into the atmosphere
- creating areas of low pressure by evapotranspiration that generate winds and draw in moisture from afar
- having an 'evaporative cooling' effect by absorbing solar energy and converting it into latent heat held in water vapour through evapotranspiration
- emission of organic aerosols, and volatile organic compounds that oxidise to form aerosols, that act as cloud condensation nuclei around which water drops form
- increasing air turbulence, causing drag on the air and reducing wind speed, increasing transfer of moisture into the air, causing updrafts and rain
- tree canopies harvesting water directly from wind and clouds, particularly in coastal and mountainous country.

The influence of vegetation is related to many variables; the prevailing climate, the vegetation type and structure, its extent, the season and time of day. It is forests. with their large canopy volume, massive evapotranspiration, deep roots and protected microclimate that are the most significant terrestrial drivers of regional climates.

Clearing vegetation can reduce rainfall by:

- reducing evapotranspiration and atmospheric moisture, causing a decrease in convective updrafts, clouds and the drawing in of moist air from afar;

- potentially increasing albedo (reflection of solar energy from the earth), having a cooling effect and causing a decrease in convective clouds;
- increasing runoff and reducing the availability of soil moisture for evapotranspiration;
- reducing rooting depth and the ability of vegetation to tap into, and recycle, groundwater;
- reducing vegetation height and surface roughness, increasing wind speed while reducing the ability of wind to capture moisture from canopies and the generation of updrafts;
- increasing surface sensible heat fluxes and decreasing latent heat fluxes, resulting is a reduction in evaporative cooling and raising the surface air temperature, causing drying; and,
- reducing organic aerosols and volatile organic compounds, and thus the availability of cloud condensation nuclei.

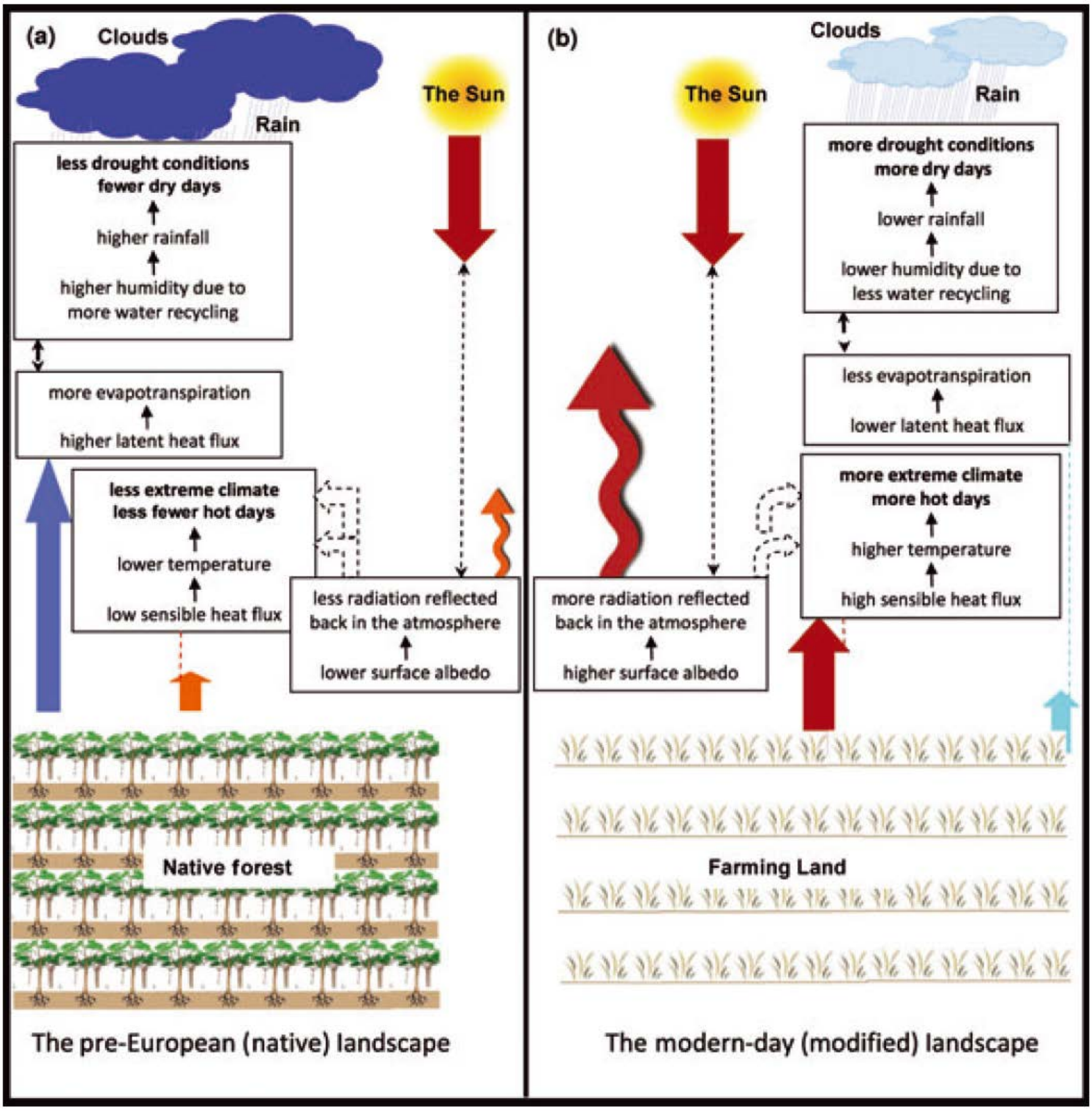


Figure 3 from Deo (2011). The impact of vegetation-cover change on surface energy balance, hydrological cycle and climate for two hypothetical landscapes: (a) pre-European (native) landscape, and (b) modern-day (modified) landscape. The coloured arrows show various energy/heat fluxes and black arrows show consequence of events or processes

An array of parameters that influence climate have now been identified in scientific studies as being significantly affected by deforestation, including evapotranspiration, vegetation rooting depth, surface roughness, canopy height, leaf area, stomatal resistance, humidity, wind, soil moisture, the ratio of latent/sensible heat, albedo, cloud cover, and snow cover (variously Shukla *et. al.* 1990, Nobre *et. al* 1991, Betts *et. al.* 1996, Claussen 1998, Zeng and Neelin 2000, Taylor *et.al.* 2002, Findell *et. al.* 2007, Findell *et. al.* 2009, Foley *et. al.* 2003, Foley *et. al.* 2003b, McAlpine *et. al.* 2009, Lawrence and Chase 2010, Bagley 2011, Kala *et. al.* 2011, Spracklen *et. al.* 2012, Pitman *et. al.* 2012, de Noblet-Ducoudré *et. al.* 2012, Andrich and Imberger 2013).

There are now numerous assessments, based on research and/or modelling, that agree that over the past few centuries and decades deforestation (Land Cover Change) has had significant biogeophysical impacts on rainfalls and/or temperatures in the regions subject to significant deforestation, for example:

> Charney 1975, Sud and Smith 1985, Claussen 1998, Shukla *et. al.* 1990, Meher-Homji 1991, Nobre *et. al* 1991, Giambelluca *et. al*. 1999, Hoffmann and Jackson 2000, Zeng and Neelin 2000, Zang et. al. 2001, Pielke 2001, Taylor *et. al.* 2002, Foley *et. al.* 2002, Lyons 2002, Gordon *et. al.* 2003, Foley *et. al.* 2003b, Narisma and Pitman 2003, Fu 2003, Hatton *et. al.* 2003, von Randow *et. al.* 2004, Pitman *et.al.* 2004, Miller *et. al* 2005, Huang *et. al.* 1995, Brovkin. *et. al.* 2006, Guo *et. al*. 2006, Makarieva and Gorshkov 2006, Timbal and Arblaster 2006, Findell *et. al.* 2007, Lam *et. al.* 2007, Syktus *et.al.* 2007, McAlpine *et. al.* 2007, Chapin III *et al*., 2008, Ramanathan and Carmichael 2008, Findell *et. al.* 2009, Pitman *et. al.* 2009, Sheil and Murdiyarso 2009, Makarieva *et. al.* 2009, McAlpine *et. al.* 2009, Makarieva and Gorshkov 2010, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Adams 2010, Deo 2011, Bagley 2011, Kala *et. al.* 2011, Ban-Weiss *et. al.* 2011, Nair *et. al.* 2011, Notaro *et. al.* 2011, Kovářová *et. al.* 2011, Lee *et. al.* 2011, Spracklen *et. al.* 2012, Pitman *et. al.* 2012, Eiseltová *et. al.* 2012, Tavares 2012, de Noblet-Ducoudré *et. al.* 2012, Rahgozar *et. al.* 2012, Wyrwoll *et. al.* 2013, Andrich and Imberger 2013, Luyssaert *et al*. 2014, Chen and Dirmeyer 2016.

The regional impacts of deforestation can be amplified during drought conditions (i.e. Bagley 2011, Pitman *et. al.* 2012).

The thinning of native vegetation, including by burning and grazing, can have proportional impacts similar to clearing (i.e. section 2.1).

The conversion of forests to regrowth has a distinctly different impact as the regrowth increases transpiration of soil moisture to the atmosphere, which reduces runoff and theoretically increases atmospheric moisture. Though logging also changes the structure of the forest (reducing its surface roughness and rooting depth) as well as causing changes in energy balances and the interior microclimate, all of which would have negative impacts on rainfall. While the effect of regrowth on runoff has been extensively studied (see section 2.4), no study of the effect of regrowth on regional rainfalls was located.

The case study of south-west Western Australia (section 2.4) shows that when combined with declining rainfalls, the increased transpiration of regrowth can have disastrous consequences for regional water supplies and the health of the forest.

In subsequent sub-sections this review considers in detail the impacts that deforestation has on climate, in relation to the principal attributes of evapotranspiration, energy fluxes, vegetation surface roughness, aerosols and soil moisture.

Another impact of deforestation having long-term climatic impacts is the release of large pulses of carbon dioxide to the atmosphere, as carbon stored in biomass such as trees and soil is released as the biomass is burned or allowed to decompose, accounting for as much as a third of total anthropogenic CO^2 emissions since 1850 (Bagley 2011). This review does not dwell on climate changes underway due to increasing atmospheric CO^2, but rather aims to identify the direct biogeophysical effects of deforestation on climate.

The surface of the earth has 130Mkm^2 of ice-free land. It is estimated that worldwide human activities have directly affected around 100Mkm^2 of this, leaving less than 30% of the land surface largely untouched, of this between 23 and 38Mkm^2 (18-29% of the land surface) has been deliberately converted, mainly by deforestation, for agriculture, infrastructure and urban use (Luyssaert *et al*. 2014). It is evident that outside the polar regions a large portion of the lands that have not yet been identified as significantly affected are the world's arid lands, which may themselves be partially attributed to the impacts of earlier civilisations (i.e. Claussen 1998, Johnson *et. al.* 1999, Brovkin 2002, Foley *et. al.* 2003, Fu 2003, Miller *et. al* 2005, Makarieva and Gorshkov 2010, Beresford-Jones *et. al.* 2009, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013).

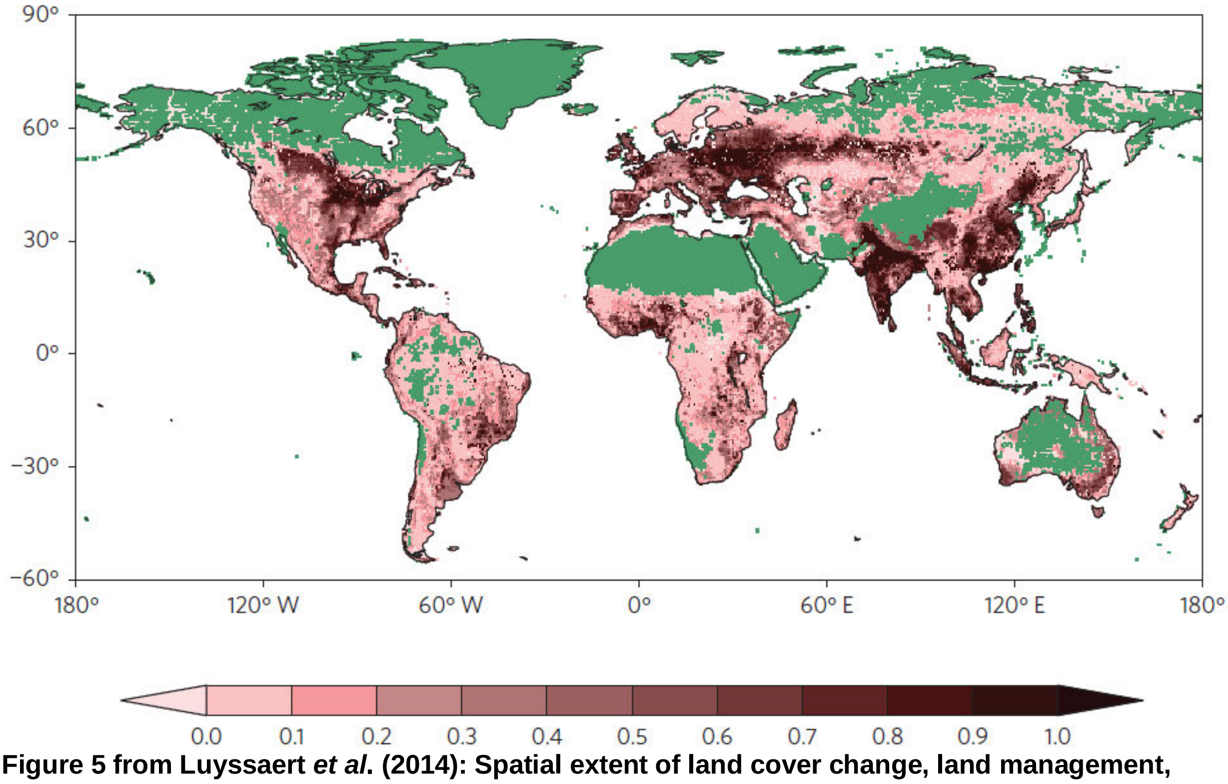


Figure 5 from Luyssaert *et al*. (2014): Spatial extent of land cover change, land management, wilderness and non-productive areas (Supplementary Section 2.3).Wilderness and non-productive areas are shown in green and represent land largely unaltered by humans in recent times. The remaining land is used for producing food, fibre and fuels, and for hosting infrastructure. The colour scale represents the fraction of each grid cell for which the original plant cover was converted. Dark colours indicate regions where most of the original plant cover was converted; these regions are the subject of typical land cover change studies. The light colours show areas for which land cover change is low, but which are nevertheless under anthropogenic land management.

There have been a large number of assessments of the likely impacts of anthropogenic Land Cover Change (LCC - clearing of native vegetation for crops, pasture or houses), and to a small extent Land Management Change (LMC - change off vegetation by logging, grazing and/or fire), on both regional climates and the world's climate. Regrettably the modelling studies use highly variable baseline data, limited variables, different assumptions of consequences, and mostly fail to account for the more extensive areas subject to degradation due to grazing, logging or increased fire regimes, and thus deliver highly variable outcomes (i.e. Pitman *et. al.* 2009, de Noblet-Ducoudré *et. al.* 2012, Luyssaert *et al*. 2014).

While some of the data is coarse, models simplistic, variables unaccounted for, and assumptions questionable, the modelling, and testing, has enabled insights into the inter-relationship between climate and vegetation. For example, from their comparison of 7 models de Noblet-Ducoudré *et. al.* 2012 found a number of robust common features, including that the changes in response to deforestation depend almost linearly on the amount of trees removed.

In general the impacts of deforestation on a global scale are often considered relatively insignificant because of the overwhelming influence of the oceans, or because minimal measures of LCC have been used in assessments (i.e. Findell *et. al.* 2007, Pitman *et. al.* 2012, Chen and Dirmeyer 2016). Though a variety of modelling studies have still identified significant global effects from LCC (i.e. Brovkin. *et. al.* 2006, Findell et. al. 2009, Luyssaert *et al*. 2014).

The complex feedback systems contributing to rainfall can come under increasing stress due to the degradation of vegetation, sometimes resulting in sudden catastrophic changes when an event triggers regime shifts. McAlpine *et. al.* (2009) consider:

> *Climate changes due to increased anthropogenic greenhouse gases coupled with land surface feedbacks appears to be amplifying the natural climate variability and has the potential to tip Australia's climate, especially in southeast Australia, into a new regime of more extensive, frequent and severe droughts. The term 'tipping' refers to a critical threshold at which a small change in the control parameters can alter the state of the climate system*

Excessive clearing has been associated with the downfall of many past civilisations. We need to learn from the lessons of history, understand and acknowledge the consequences of deforestation, and stop the desertification of Australia.

1.1. Evapotranspiration

The atmosphere receives vast inputs of water vapour as evaporation from the oceans and land, as well as transpiration by vegetation. This water vapour is returned to earth as rainfall, with the water in the atmosphere turned over about 34 times every year.

Evapotranspiration is used to account for the evaporation of water from the ground and wet vegetation, along with the conversion of water to vapour through the process of transpiration by plants. Transpiration involves the transport of water (and nutrients) from roots to leaves, where it is released by evaporation to the atmosphere through stomata on leaves.

By one estimation, evapotranspiration across the global land surface (excluding water bodies and permanent ice surfaces) is 63,200 km^3yr^{-1}, which is 67% of mean annual rainfall (Zhang *et. al.* 2016), with the balance being transported back to the oceans by rivers, or diverted into deep aquifers. Transpiration by plants is responsible for recycling huge volumes of water and thus significantly contributes to atmospheric moisture, clouds and resultant rainfall. Transpiration is considered to be responsible for around 65% of evapotranspiration, evaporation from wet vegetation around 10%, and evaporation from the soil for around 25% (Zhang *et. al.* 2016). Miralles *et. al.* (2010) put the evaporation from forests as being higher, identifying that canopy interception of rainfall is responsible for the evaporation of approximately 13% of the total incoming rainfall over broadleaf evergreen forests, 19% in broadleaf deciduous forests, and 22% in needleleaf forests.

Van der Ent *et. al* (2010) consider that "*It is computed that, on average, 40% of the terrestrial precipitation originates from land evaporation and that 57% of all terrestrial evaporation returns as precipitation over land*". It has been found in the Amazon that evapotranspiration from forests accounts for more than 50% of rainfall (Nobre *et. al* 1991, Spracklen *et. al.* 2012)

The amount of water that can be recycled by evapotranspiration from vegetation is related to canopy volume (the area of leaves -Leaf Area Index) and root depth (the ability to access deeper water sources), thus it is tall forests with their large canopies and deep roots that provide the highest rate of evapotranspiration. When vegetation is cleared there is a reduction in surface area for evaporation, reduced transpiration, increased runoff and a reduced ability to access deeper soil moisture. By reducing evapotranspiration, deforestation results in less water being pumped into the atmosphere, thereby directly contributing to a decrease in rainfall (Shukla *et. al.* 1990, Nobre *et. al* 1991, Spracklen *et. al.* 2012, Andrich and Imberger 2013).

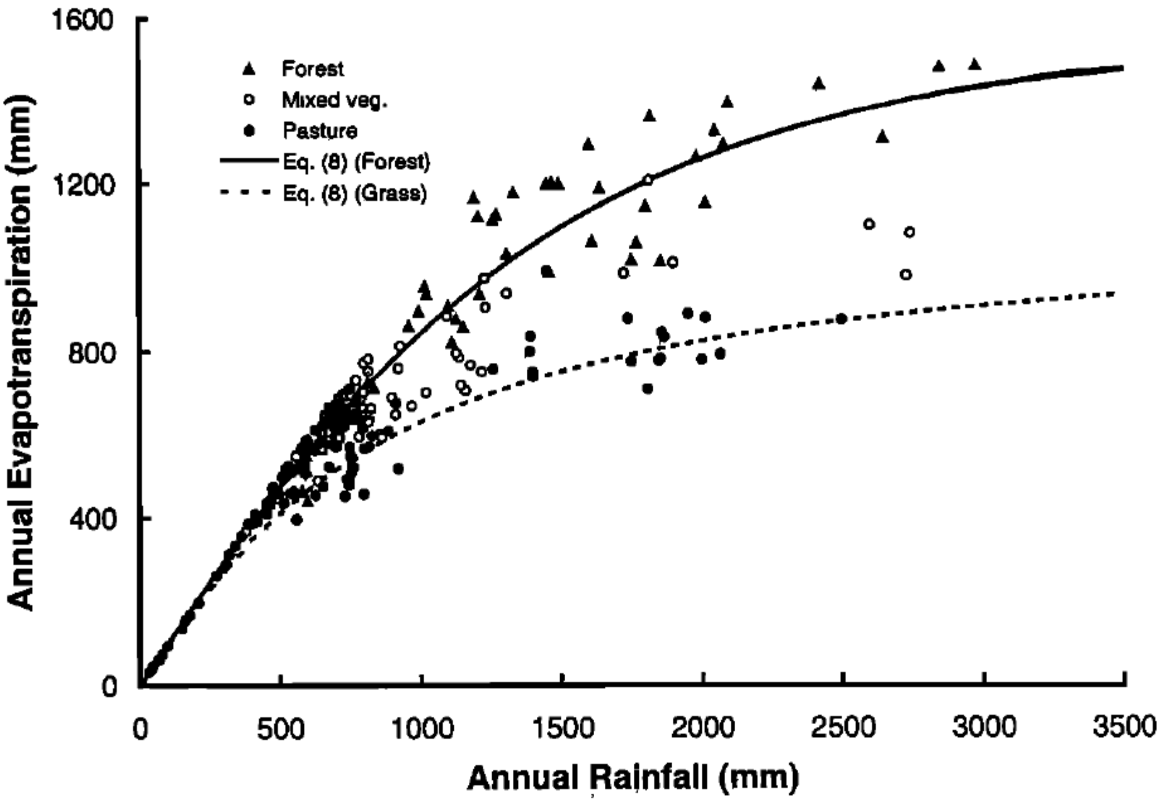


Figure 9 from Zang *et. al.* (2001): generalised relationship between annual evapotranspiration and rainfall for different vegetation types. The difference between the grass and forest curve represents the change in mean annual water yield for a 100% change in vegetation for a given mean annual rainfall.

In comparison to large canopied and deeply rooted woody vegetation, grasslands and crops only have small leaf areas and shallow rooting structures and thus lower evapotranspiration. They have less resources to tap in times of drought. Annual crops only transpire water during part of the year. They do not capture as much rainfall and soil moisture as the native vegetation, meaning less water vapour is returned to the atmosphere to be available for precipitation.

From their comparison of Amazonian pasture and rainforest, von Randow *et. al.* (2004) found that in the wet season "*evapotranspiration rates are 20% lower in the pasture, compared to the forest",* and in the dry season evapotranspiration *"rates are 41% lower in the pasture".*

Zang *et. al.* (2001) consider that "*Under dry conditions the principal controls on evapotranspiration are plant-available water and canopy resistance. Under wet conditions the dominant controls are advection, net radiation, leaf area, and turbulent transport. Under intermediate conditions the relative importance of these factors varies depending on climate, soil, and vegetation*". Zang et. al. (2001) developed a generalised model for vegetation evapotranspiration, noting "*in spite of the complexity of the soil-vegetation-atmosphere system the most important factors controlling mean annual evapotranspiration appear to be annual rainfall, potential evapotranspiration, and vegetation type*".

Most of the rain that falls upon a forest is recycled to the atmosphere through evapotranspiration, where it again becomes available for rainfall. Water may be recycled numerous times as it passes over the land before it returns to the oceans in streamflows or as rainfall. This process is vital for maintaining rainfall over inland areas.

From their analyses of tropical land surface (latitudes 30 degrees south to 30 degrees north) Spracklen *et. al.* (2012) found that for more than 60 per cent of the land air that has passed over extensive vegetation in the preceding few days produces at least twice as much rain as air that has passed over little vegetation. noting:

> *... additional moisture from evapotranspiration emitted into air masses with large exposure to vegetation is substantially greater than the additional precipitation observed in these air masses. Indeed, for all four regions the extra* [cumulative surface evaporation] *emitted into air masses with large vegetation exposure exceeds the observed additional precipitation by a factor of at least four...*
>
> *Through evapotranspiration, forests maintain atmospheric moisture that can return to land as rainfall downwind. These processes operate on timescales of days over distances of 100–1,000km ...such that large-scale land-use change may alter precipitation hundreds to thousands of kilometres from the region of vegetation change.*

In the central Amazon basin over half of the precipitated water goes back into the atmosphere through evapotranspiration, while approximately 45 percent are drained by rivers back to the ocean (Tavares 2012). Moisture-laden winds from the Atlantic Ocean account for 52 percent of the rainfall, with the balance recycled by the vegetation (Tavares 2012).

Nobre *et. al* (1991) identify that the main source of water vapour to the Amazon is the Atlantic Ocean, though in western Amazonia 2,000-3,000 km inland the water column apparently has more water vapour than near the Atlantic coast, commenting "*recycling of water vapor through evapotranspiration is clearly very important*".

Van der Ent *et. al* (2010) identify that local moisture recycling is a feature of some regions, though in most regions the majority of rainfall originates from elsewhere, for example:

> *Moisture evaporating from the Eurasian continent is responsible for 80% of China's water resources. In South America, the Río de la Plata basin depends on evaporation from the Amazon forest for 70% of its water resources. The main source of rainfall in the Congo basin is moisture evaporated over East Africa, particularly the Great Lakes region. The Congo basin in its turn is a major source of moisture for rainfall in the Sahel*.

It is important to consider that clearing forests in one region can have significant adverse impacts on rainfall in another region. Van der Ent *et. al.* (2010) consider:

> *Our results suggest that decreasing evaporation in areas where continental evaporation recycling is high (e.g., by deforestation), would enhance droughts in downwind areas where overall precipitation amounts are low. On the other hand, water conservation in these areas would have a positive multiplier effect on rainfall downwind.*

Sheil and Murdiyarso (2009) consider:

> *The world's hydrological systems are changing rapidly. Food security in many regions is heavily threatened by changing rainfall patterns (Lobell et al. 2008). Meanwhile, deforestation has already reduced vapor flows derived from forests by almost five percent (an estimated 3000 cubic kilometers [km^3] per year of a global terrestrial derived total of 67,000 km^3), with little sign of slowing (Gordon et al. 2005). The need for understanding how vegetation cover influences climate has never been more urgent.*

1.1.1. Forests as Biotic Pumps

Bernardin de Saint Pierre (1784-8) was not alone in the 18th century with his observation "*This attractive force of the forests on this island is such that a field in an uncovered situation close to them often suffers a lack of rain whereas it rains almost all year long in woods that are situated within gunshot".* It has long been observed that vegetation attracts rainfall, rather than simply being a product of it. More recent studies have confirmed such observations, though the mechanisms are still poorly understood,

It is apparent that vegetation has an ability to attract rainfall to itself even in semi-arid environments. For their study area in central Africa, Los *et. al.* (2006) identified "*positive feedback between vegetation and rainfall at the monthly time scale, and for a vegetation memory operating at the annual time scale*", noting "*These vegetation-rainfall interactions increase the interannual variation in Sahelian precipitation; accounting for as much as 30% of the variability in annual precipitation in some hot spot regions*".

In the Kalahari of southern Africa Chikoore and Jury (2010) found a flush of vegetation resulting from a rain event "*'draws' airflow toward itself in a self-sustaining way*", noting:

> *An increase in vegetation appears to draw the airflow toward itself, enhancing the low-level buoyancy and slowing the winds through friction, thereby causing convergence and uplift. Thus vegetation seems to impact horizontal momentum transfer as much as vertical moisture flux.*

A variety of studies in tropical environments have identified that rainfall can decline following deforestation by more than the reduction in evapotranspiration can account for, indicating that there is a reduction of moisture influxes into a region following deforestation. From their observations and modelling in the Amazon, Shukla *et. al.* (1990) concluded:

> *The reduction in calculated annual precipitation by 642 mm and in evapotranspiration by 496 mm suggests that changes in the atmospheric circulation may act to further reduce the convergence of moisture flux in the region ...*
>
> *... a reduction in evaporation might be compensated for by an increase in moisture flux convergence. Our experiments indicate that such a compensation will not occur for the Amazon and that there is even a further decrease in convergence of the large-scale moisture flux.*
> *...*
> *The most significant result of this study is the simulated reduction in precipitation over Amazonia, which is larger than the corresponding regional reduction in evapotranspiration, implying that the dynamical convergence of moisture flux also decreased as a result of deforestation.*

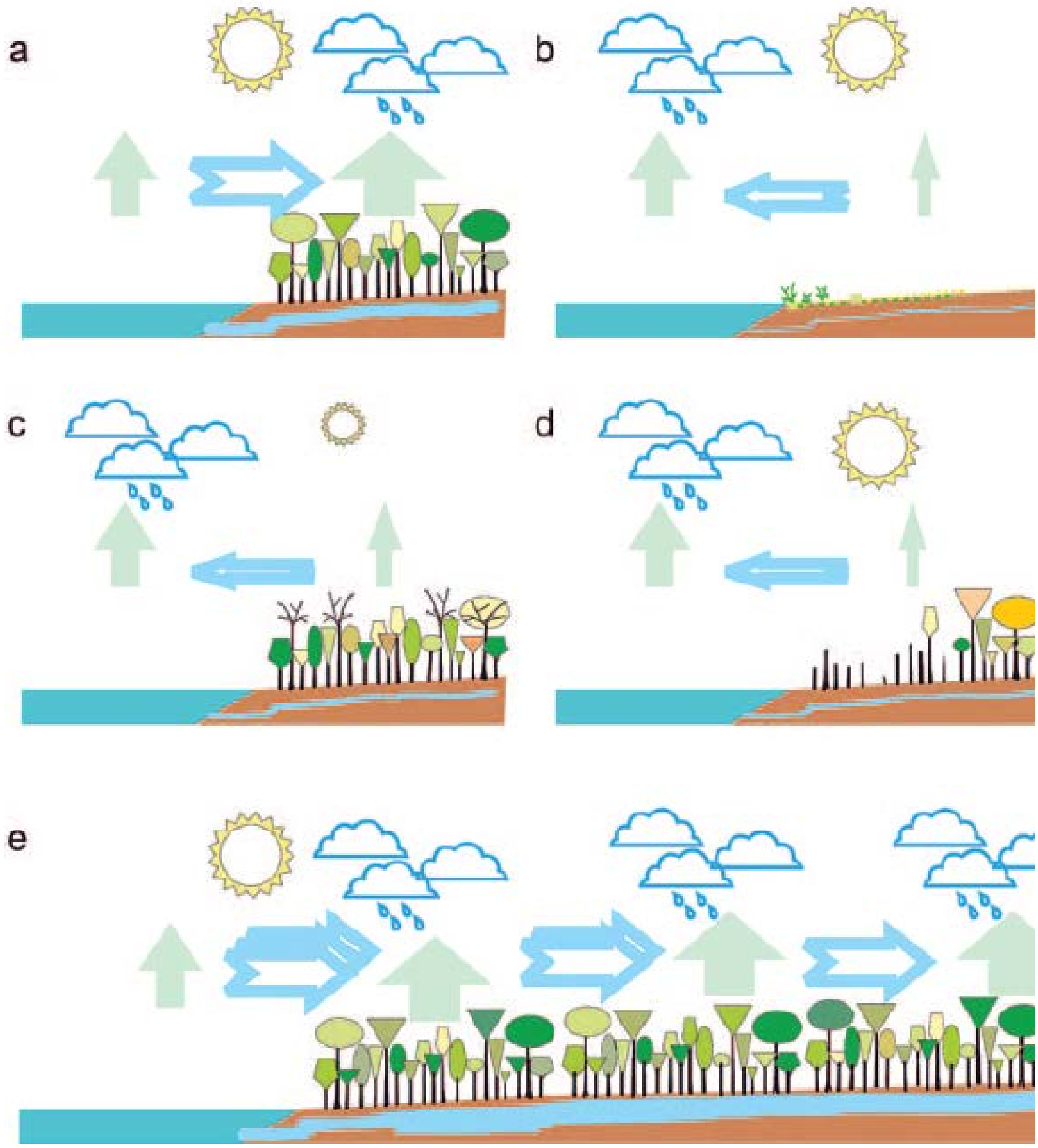
From their studies of the Amazon, Nobre *et. al* (1991) concluded "*The calculated reduction in precipitation was larger than the calculated decrease in evapotranspiration, indicating a reduction in the regional moisture convergence*".

In their modelling of the impact of conversion of savannas to grasslands, Hoffmann and Jackson (2000) found "*precipitation declined more than did evapotranspiration, indicating a reduction in moisture convergence (Table 2). Moisture convergence, that is, the net flux of water vapor into a region, has similarly been found to decline in most tropical deforestation simulations*".

It has been postulated that forests play a crucial role in hydrological cycles by acting as the Biotic Pump of atmospheric moisture (Makarieva and Gorshkov 2006, Makarieva *et. al.* 2009, Makarieva and Gorshkov 2010, Sheil and Murdiyarso 2009). From their study, Makarieva and Gorshkov (2006, 2009) concluded that the mean distance that the atmosphere can transport moisture inland over non-forested land does not exceed several hundred kilometers, with precipitation decreasing exponentially with distance from the ocean. They note that in contrast, precipitation over extensive natural forests does not depend on the distance from the ocean along several thousand kilometers.

Makarieva and Gorshkov (2006) found that areas with strong evaporation/transpiration draw in moisture from areas with low evaporation, thereby enhancing rainfall. Makarieva and Gorshkov (2006) postulated that natural forests are the biotic pump of atmospheric moisture:

> *Due to the high leaf area index, natural forests maintain powerful transpiration exceeding evaporation from the oceanic surface. The transpiration flux supports ascending fluxes of air and “sucks in” moist air from the ocean. In the result, forest precipitation increases up to a level when the runoff losses from optimally moistened soil are fully compensated at any distance from the ocean.*
>
> *Natural forest ecosystems, with their high leaf area index and high transpiration exceeding evaporation from open water surface, are capable of pumping atmospheric moisture from the ocean in amounts sufficient for the maintenance of optimal soil moisture stores, compensating the river runoff and ensuring maximum ecosystem productivity.*



An illustration of the biotic pump, from Sheil and Murdiyarso (2009): Atmospheric volume reduces at a higher rate over areas with more intensive evaporation solid vertical arrows, widths denotes relative flux). The resulting low pressure draws in additional moist air (open horizontal arrows) from areas with weaker evaporation. This leads to a net transfer of atmospheric moisture to the areas with the highest evaporation. (a) Under full sunshine, forests maintain higher evaporation than oceans and thus draw in moist ocean air. (b) In deserts, evaporation is low and air is drawn toward the oceans. (c) In seasonal climates, solar energy may be insufficient to maintain forest evaporation at rates higher than those over the oceans during a winter dry season, and the oceans draw air from the land. However, in summer, high forest evaporation rates are re-established (as in panel a). (d) With forest loss, the net evaporation over the land declines and may be insufficient to counterbalance that from the ocean: air will flow seaward and the land becomes arid and unable to sustain forests. (e) In wet continents, continuous forest cover maintaining high evaporation allows large amounts of moist air to be drawn in from the coast. Not shown in diagrams: dry air returns at higher altitudes, from wetter to drier regions, to complete the cycle, and internal recycling of rain contributes significantly to continental scale rainfall patterns. Source: Adapted from ideas presented in Makarieva and Gorshkov (2007).

A review of the Biotic Pump theory by Sheil and Murdiyarso (2009) concluded:

> *The underlying mechanism emphasizes the role of evaporation and condensation in generating atmospheric pressure differences, and accounts for several phenomena neglected by existing models. It suggests that even localized forest loss can sometimes flip a wet continent to arid conditions. If it survives scrutiny, this hypothesis will transform how we view forest loss, climate change, hydrology, and environmental services. It offers new lines of investigation in macroecology and landscape ecology, hydrology, forest restoration, and paleoclimates. It also provides a compelling new motivation for forest conservation.*
>
> *...*
>
> *Researchers have previously puzzled over a missing mechanism to account for observed precipitation patterns (Eltahir 1998). Makarieva and Gorshkov's hypothesis offers an elegant solution: they call it a "pump."*
>
> *...*
>
> *Conventional models typically predict a "moderate" 20 to 30 percent decline in rainfall after continental-scale deforestation (Bonan 2008). In contrast, Makarieva and Gorshkov suggest that even relatively localized clearing might ultimately switch entire continental climates from wet to arid, with rainfall declining by more than 95 percent in the interior.*

For the biotic pump to provide more inland rainfall, vegetation transpiration fluxes need to exceed the fluxes of evaporation from the open water surface of the ocean. The strength and effectiveness of the biotic pump, and thus inland rainfall, is dependent on the number of trees in the forest and the area of the forest-cover. Makarieva and Gorshkov (2006) found that "*Replacement of the natural forest cover by a low leaf index vegetation leads to an up to tenfold reduction in mean continental precipitation and runoff*", also noting:

> *The biotic moisture pump, as well as the mechanisms of efficient soil moisture preservation ... work in undisturbed natural forests only. Natural forest represents a contiguous cover of tall trees that are rigidly associated with other biological species of the ecological community and genetically programmed to function in the particular geographic region. The vegetation cover of grasslands, shrublands, savannas, steppes, prairies, artificially thinned exploited forests, plantations, pastures or arable lands is unable to switch on the biotic moisture pump and maintain soil moisture content in a state optimal for life. Water cycle on such territories is critically dependent on the distance from the ocean; it is determined by random fluctuations and seasonal changes of rainfall brought from the ocean. Such territories are prone to droughts, floods and fires.*
>
> *... If the natural forest cover is eliminated along the oceanic coastline on a band* [around] *600 km wide, the biotic moisture pump stalls. The remaining inland forests are no longer able to pump atmospheric moisture from the ocean. There is no longer surplus to runoff to rivers or to recharge groundwater. ...*
>
> *...*
>
> *The results obtained form the basis of a possible strategy to restore human-friendly water conditions on most part of the Earth's landmasses, including modern deserts and other arid zones. As we have shown, elimination of the forest cover in world's largest river basins would have the following consequences: at least one order of magnitude's decline of the river runoff, appearance of droughts, floods and fires, partial desertification of the coastal zone and complete desertification of the inner parts of the continents, ...associated economic losses would by far exceed the economic benefits of forest cutting ... Therefore, it is worthy to urgently reconsider the modern forest policy everywhere in the world. First of all, it is*

> *necessary to immediately stop any attempts of destroying the extant natural forest remnants and, in particular, those bordering with the ocean or inner seas. Further on, it is necessary to initiate a world-wide company on facilitating natural gradual recovery of aboriginal forest ecosystems on territories adjacent to the remaining natural forests. Only extensive contiguous natural forests will be able to run a stable water cycle and subsequently intensify it, gradually extending the river basin at the expense of newly recovering territories.*

Makarieva and Gorshkov (2006) conclude:

> *Forests are responsible both for the initial accumulation of water on continents in the geological past and for the stable maintenance of the accumulated water stores in the subsequent periods of life existence on land. ... It is shown that only intact contiguous cover of natural forests having extensive borders with large water bodies (sea, ocean) is able to keep land moistened up to an optimal for life level everywhere on land, no matter how far from the ocean.*

1.2. Energy Fluxes

Incoming solar energy (shortwave radiation) can be reflected back into space (mostly off clouds or by the earth's surface) or absorbed in the atmosphere (mainly by oxygen, ozone and water vapour). The fraction of solar energy that is reflected is determined by the surface albedo, which depends on the optical properties of the surface.

Around half the incoming solar energy is absorbed by the earth's surface, vegetation and waters. The solar energy can either heat the surface and raise its temperature (sensible heating) or it can change the phase of water from liquid to vapour (evaporate) without a corresponding temperature change (latent heating). Latent refers to the heat which "disappears" without causing a temperature change.

A large portion of this surface energy transported back into the atmosphere as “radiative” fluxes and “turbulent” fluxes. The turbulent fluxes are associated with wind replenishing air at the surface-atmosphere interface; turbulent sensible heat-fluxes (associated with convection) are driven by the difference in temperatures between the surface and the atmosphere, and turbulent latent heat fluxes (e.g. evaporation) are driven by difference in vapour pressure between surface and atmosphere.

The atmosphere is heated by heat emitted from sunlight-warmed surfaces and heat released by condensation of water vapour, and cooled by radiation re-emitted both upwards and downwards. Water vapour is nearly opaque at the long wavelengths at which the surface radiates away its absorbed energy. The absorption of most of the outgoing thermal radiation by water vapour creates most of Earth's natural greenhouse effect. By reducing heat losses from the earth's surface, atmospheric gases and aerosols keep the earth around 33°C warmer than it otherwise would be. Atmospheric water vapour is the dominant contributor to the greenhouse effect, contributing up to 60% of the total radiative forcing compared to carbon dioxide's 26% (Kiehl and Trenberth 1997).

Rainfall occurs because as air heats it takes up more water vapour and begins to rise, as it rises it cools (by roughly one degree centigrade for every 100m of altitude in dry air), as the air cools cloud droplets begin to form around aerosols such as dust, sea salt, bits of organic matter, or chemical aerosol particles, as the water condenses its stored heat is released.

Water has a high capacity for the storing and transporting of heat and so is able to redistribute much of the solar heat energy through the water cycle. By its regulation of evapotranspiration and condensation vegetation has a profound influence on the water cycle, and thus plays a key role in earth's energy budget.

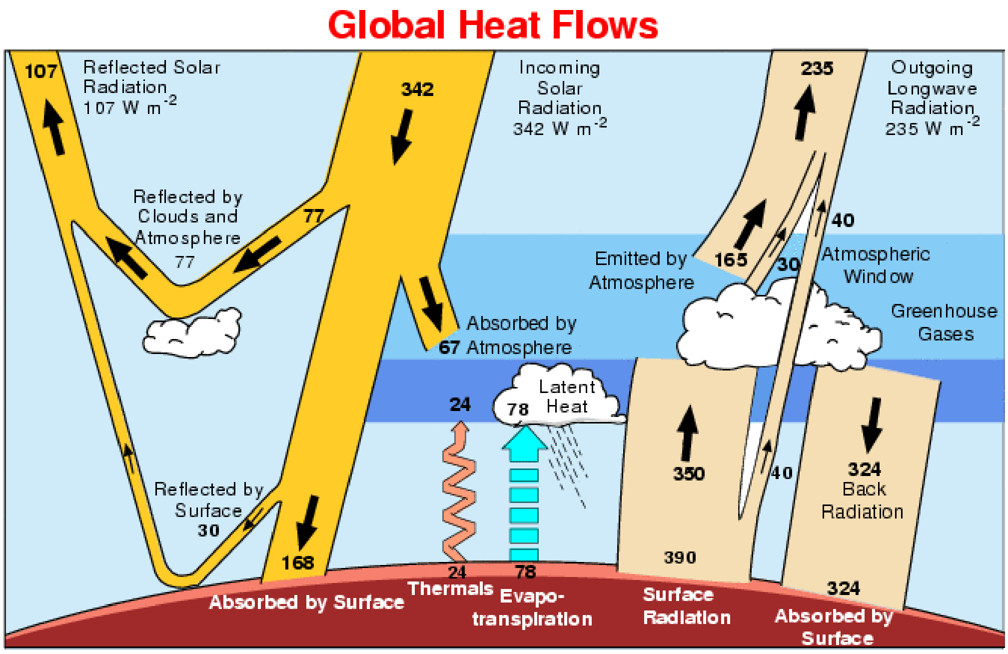


Figure 7, adapted from Kiehl and Trenberth (1997) The earth's annual global mean energy budget based on the present study. Units are W m^{-2}.

When vegetation is cleared, the direct feedbacks include alterations of absorbed solar radiation due to albedo changes, and perturbations to the partitioning of net radiation between sensible, latent and ground heat.

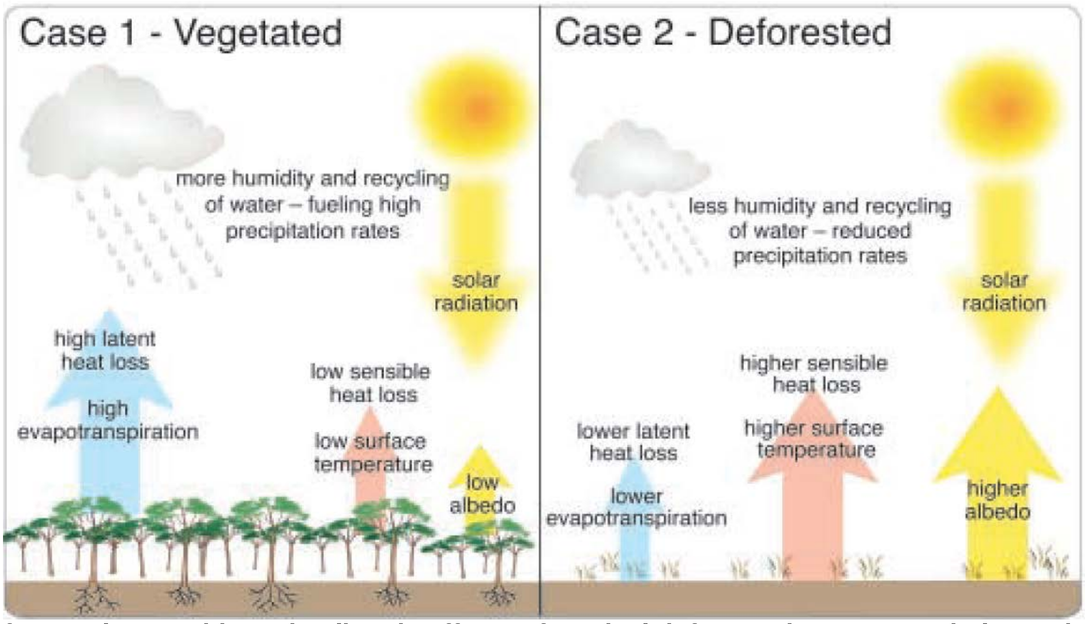


Figure 2 from Foley *et. al.*(2002): Climatic effects of tropical deforestation on water balance, boundary layer fluxes, and climate. In vegetation-covered areas (left), the low albedo of the forest canopy provides ample energy for the plants to photosynthesize and transpire, leading to a high latent heat

loss that cools the surface. In deforested areas (right), bare soil's higher albedo reduces the amount of energy absorbed at the surface. Latent heat loss is severely reduced and the surface warms, as it has no means of removing the excess energy through transpiration.

1.2.1. Albedo

The amount of solar energy reflected back into space by a surface is referred to as its albedo. Albedo is the percentage of radiation the surface reflects. Changes in surface albedo due to deforestation has been considered by some researchers to be one of the main drivers of climate responses.

One effect of deforestation is the change in surface albedo. If the resulting surface is lighter coloured and more reflectent, more incoming solar energy is reflected, cooling the surface. If the surface is darker more energy is absorbed. White surfaces, such as snow and ice, have a high albedo (60-90% of solar energy reflected), sand has a moderate albedo (30-45%), bare soil a variable albedo (5-40%, depending on wetness and soil colour) and vegetation a low albedo: forests (8-20%), agricultural crops (18-25%) and grasslands (16-26%). Depending on their density, clouds also have a high albedo (30-90%).

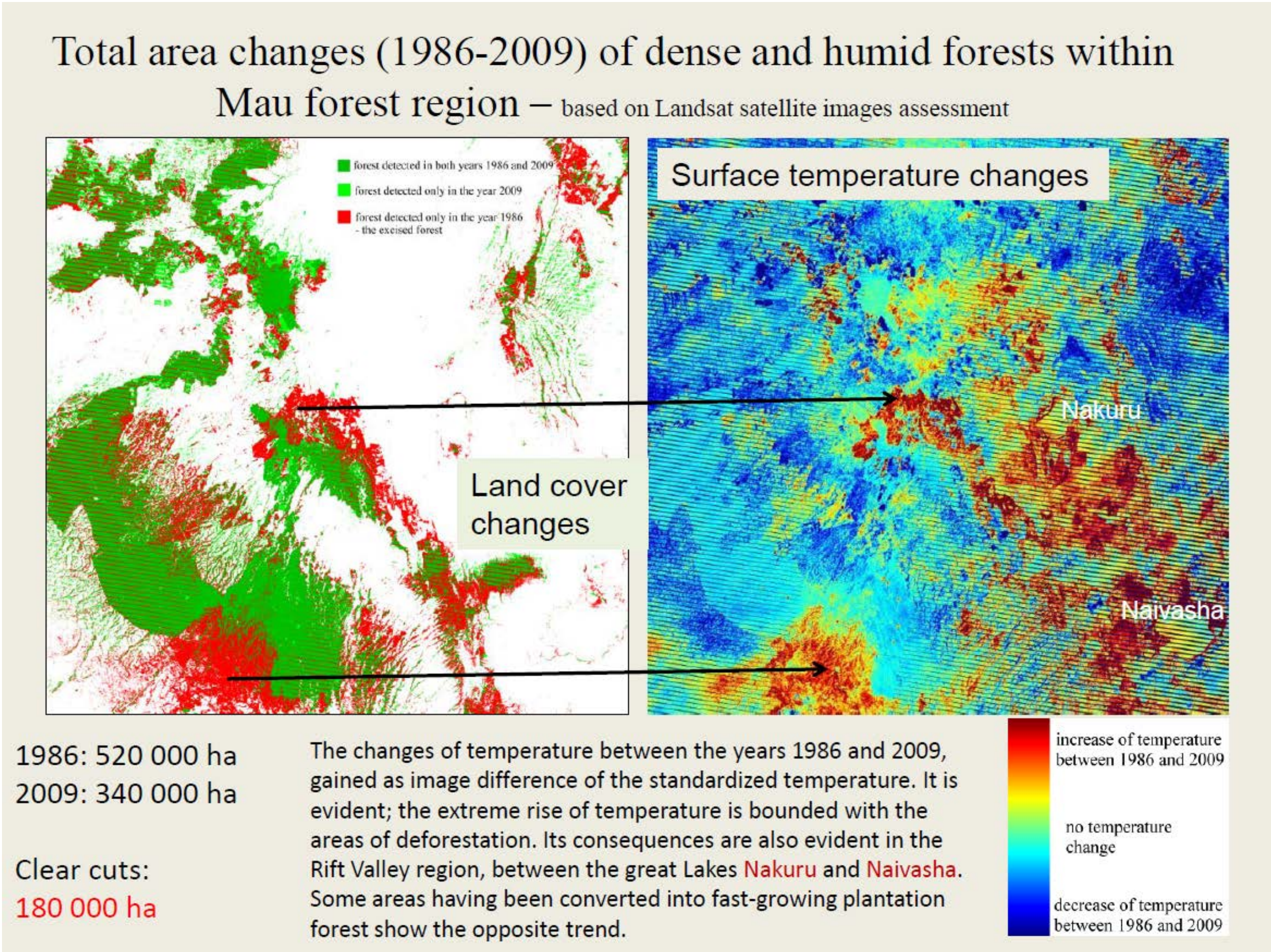
In temperate areas the increase in albedo resulting from deforestation is generally considered to have a cooling climatic effect, this is because grasses, crops and bare soils can have a higher albedo, though the primary response is considered to relate to the removal of canopy over snow increasing albedo and the feedback of reduced temperatures extending snow cover. In tropical areas the albedo effect is considered to be offset by the loss of the evaporative cooling effect of the removed vegetation and the reduction in cloud cover with its high albedo, resulting in a warming effect. (i.e. Sud and Smith 1985, Meher-Homji 1991, Nobre *et. al* 1991, Claussen 1998, Sud *et. al.* 1998,, Giambelluca *et. al*. 1999, Hoffmann and Jackson 2000, Brovkin 2002, Foley *et. al.* 2003b, von Randow *et. al.* 2004, Brovkin. *et. al.* 2006, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Deo 2011, Pitman *et. al.* 2012, Chen and Dirmeyer 2016).

Though the increase in albedo, and thus reduced temperatures, resulting from deforestation has been questioned (Eiseltová *et. al.* 2012, Chen and Dirmeyer 2016). From their comparisons of thermal satellite images in Europe and Africa Eiseltová *et. al.* (2012) identified significant increases in ground temperatures from deforestation, noting that in Kenya deforestation from 1986-2009 resulted in "*Extreme rises in temperature (by more than 20° C ...)*", and concluding "*Sites with bare ground undoubtedly belong to the warmest places in the landscape; due to the lack of water evapotranspiration, more solar energy is transformed into sensible heat (raising the site's temperature) than into latent heat of water vapour. The higher albedo of bare ground (concrete, etc.) and the lower albedo of forests does not play such an important role when compared to the cooling effect of evapotranspiration*".

In the Amazon, von Randow *et. al.* (2004) found that pasture had a significantly higher albedo than rainforest, noting "*For the radiation balance, the reflected short wave radiation increases by about 55% when changing from forest to pasture. Combined with an increase of 4.7% in long wave radiation loss, this causes an average reduction of 13.3% in net radiation in the pasture, compared to the forest*", and "*long-wave balance was a more important determinant of seasonal variations of the net radiation, than the albedo*".

Also contrary to accepted wisdom, from their study Luyssaert *et al*. (2014) observed that an increase in albedo was related to an increase in surface temperature, commenting it "*may seem paradoxical if less energy is available for surface heating following an increase in albedo*". Further investigations confirmed their opinion, "*Across all paired observations, the potential for cooling the surface due to an increase in albedo ... was outweighed by the potential for warming due to decreased fluxes of sensible heat ... but not latent heat ... For the sites under study, sensible heat and changes in sensible heat thus seem to be key drivers of the surface temperature and its changes following* [Land Cover Change] *or* [Land Management Change]". They conclude:

> *our study reveals that changes in sensible heat flux outweigh changes in albedo and underlie surface temperature changes in the temperate zone following both LCC and LMC.*



Based on comparisons of surface temperature change from forest to open land at paired observation sites, Chen and Dirmeyer (2016) identified that in summer deforestation leads to an observed daytime warming (+2.23±0.94 K) and a cooling effect at night (−2.05±1.02 K), with albedo only having a minor effect:

> *The radiation term has a slight cooling effect during day (−0.08±0.07 K), attributable to albedo change cooling being nearly offset by more infrared radiation from the warmer surface. Ground heat flux shows a warming effect during nighttime (0.18±0.12 K).*

From their modelling Lawrence and Chase (2010) identified that clearing of native vegetation results in "*year round warming of the near surface atmosphere in tropical and subtropical regions, and the winter cooling and summer warming in higher northern latitudes*".

In relation to tropical deforestation Foley et. al. (2003b) note:

> *First, the increase in albedo tends to cool the surface, by reducing the amount of solar radiation it can absorb. However, surface roughness, leaf area, and root depth are lower in pastures than in forests; this dramatically reduces evapotranspiration from the smoother surface, which in turn substantially increases its temperature. As a result, the cooling effect of the higher albedo is completely offset, and often surpassed, by the reduction in evaporative cooling. The net effect is a warming of approximately 1–2 °C in tropical regions undergoing large-scale deforestation*

Deo (2011) considers:

> *A higher surface albedo should result in a cooler surface because less radiation is absorbed. However, since modified landscapes (e.g. farming areas) have lower vegetation fraction, leaf-area index and rooting depths, this dramatically reduces evapotranspiration rates relative to native forests. As a result of reduction in evaporative cooling, less heat escapes from the land surface causing an increase in mean surface temperatures*
>
> *Changes in surface albedo can also contribute to changes in mean rainfall. The increase in surface albedo for modified land-cover conditions could produce a drier lower atmosphere, suppressing the formation of convective clouds and raindrops*

Hoffmann and Jackson (2000) note that an increase in albedo can reduce convection by reducing heat flux into the lower atmosphere. In their simulation of Monsoon rainfalls over India, Sud and Smith (1985) found the influence of increasing albedo "*was to reduce rainfall over India*". For south-east Queensland Cottrill (2009) found "*albedo affected rainfall in this region, with higher albedo leading to lower rainfall over pastoral and agricultural regions west of the Great Dividing Range*".

1.2.2. Redistributing Solar Energy

Conversion of solar energy absorbed by the earth's surface into latent heat (without a rise in temperature) by evaporation is an integral part of the climate system, linking the surface energy balance to the hydrological cycle. When water changes from a liquid to its gaseous phase energy is stored in the water vapour in the form of latent heat and produces evaporative cooling. Water vapour fluxes transport latent heat from the location where water evaporates to where the water condenses, often in clouds. The increase in clouds associated with increased evaporation increases reflection of solar radiation and thereby causes a surface cooling.

The conversion of liquid water into vapour by transpiration has been estimated to require roughly half of all solar energy absorbed by the continents (Jasechko *et. al.* 2013). Evapotranspiration thus has a cooling effect on climate, which is reinforced by the formation of clouds with their higher albedo.

Because of their deep roots, deep canopies and large leaf areas, forests are the most effective vegetation at maximising evapotranspiration, giving forests a greater latent heat flux relative to sensible heat flux than grasslands or crops.

The partitioning between ecosystem latent and sensible heat fluxes is critical in determining the hydrological cycle, boundary layer development, weather and climate (Wilson *et al.* 2002).

Deforestation results in a net decrease in evapotranspiration and thus latent heat, making more energy available for sensible heat flux and increasing the surface temperature. The reduced transpiration decreases atmospheric moisture and cloud cover. The increase in sensible heat means more longwave radiation leaving the earth's surface and, because of the reduced low cloud cover, less of this radiation is returned to the surface. The reduced cloud cover means more shortwave radiation can reach the earth's surface.

By reducing evapotranspiration, deforestation tends to cause an increase in sensible heat and surface temperatures (Shukla *et. al.* 1990, Pielke 2001, Foley *et. al.* 2003b, von Randow *et. al.* 2004, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chase 2010, Davin and de Noblet-Ducoudré 2010, Kovářová *et. al.* 2011, Deo 2011, Lee *et. al.* 2011, Bagley 2011, Ban-Weiss *et. al.* 2011, Pitman *et. al.* 2012, Eiseltová *et. al.* 2012). Kovářová *et. al.* (2011) found "*The air temperature increases at areas where a decline of available water occurs and latent heat of evapotranspiration shifts to sensible heat*". Pielke 2001 consider "*Once the surface energy budget is altered, fluxes of heat, moisture, and momentum within the planetary boundary layer are directly affected"*.

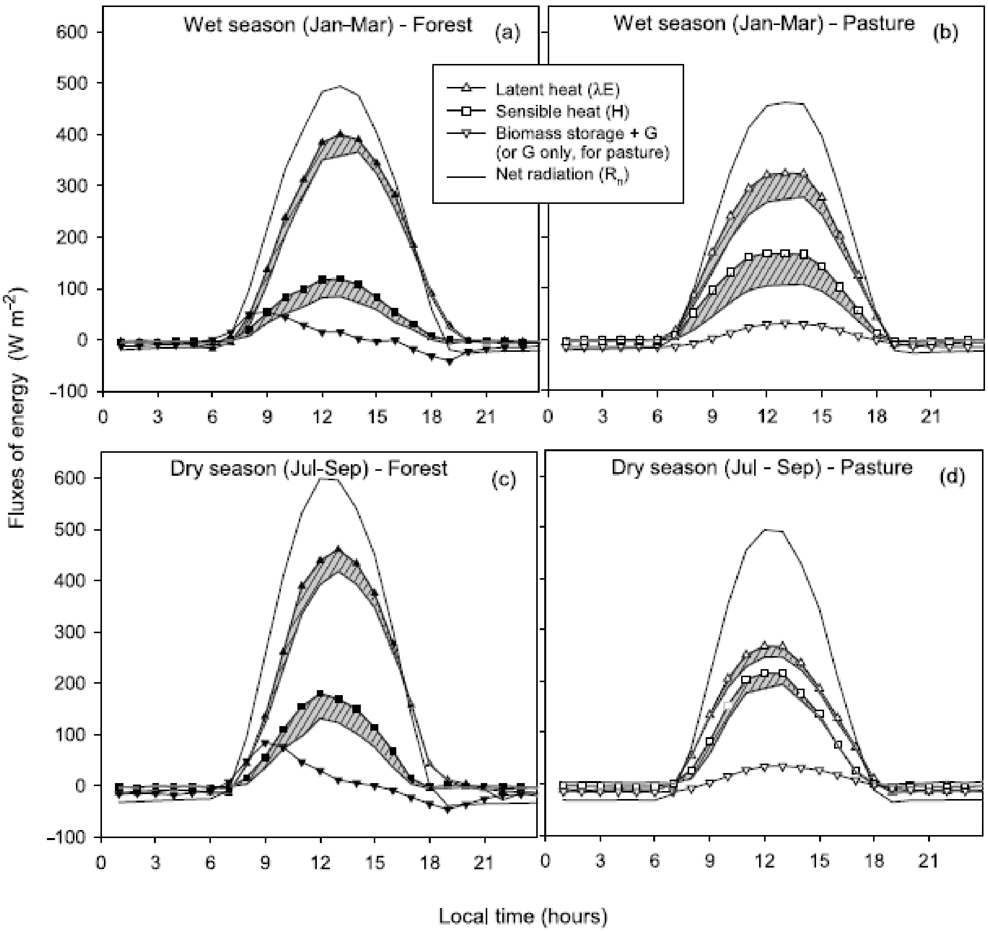


Fig. 9. from Von Randow *et. al.* (2004): Average daily patterns of net radiation (Rn), sensible and latent heat fluxes (H and \E respectively) and soil heat fluxes (+ heat storage in canopy at forest), for: (a) wet season at forest; (b) wet season at pasture; (c) dry season at forest and (d) dry season at pasture. Dashed areas represent the ranges of heat fluxes calculated using two different procedures.

Von Randow *et. al.* (2004) undertook comparisons of energy fluxes in Amazonian pasture and rainforest, finding:

> *The radiation flux components are markedly different between the two sites. The most important changes occur in the reflected short wave radiation, which increases about 55% when changing from forest to pasture. Combined with an increase of 4.7% on long wave*

> *radiation loss, this causes an average reduction of 13.3% in the net radiation in the pasture, compared to the forest....*
>
> *Large differences between the two types of surface are also noticed in the energy partition between sensible and latent heat fluxes. In the wet season the sensible heat fluxes are 45% higher, while the evapotranspiration rates are 20% lower in the pasture, compared to the forest. In the dry season, the differences are lower in the sensible heat (fluxes are 28% higher in the pasture), while the changes in evapotranspiration are large (rates are 41% lower in the pasture).*

From their modelling of the effect of land-clearing on heat fluxes, Ban-Weiss *et. al.* (2011) identifies that historical deforestation has reduced the latent heat flux on land on the order of half a watt per meter square (W m^{-2}) averaged over all land, with changes up to about 20 W m^{-2} for specific locations and seasons, noting "*studies suggest that a reduction in latent heat increases local surface temperatures due to the loss of evaporative cooling*".

However they consider that " *On the global scale, changes in surface evaporative cooling are largely compensated by changes in condensation of the water vapor in the atmosphere ... Thus, changes in latent heating do not directly affect the global energy balance. Therefore, global temperature changes are caused by changes in atmospheric properties such as water vapor content, clouds and the vertical temperature profile*". Finding that "*When increasing upward latent heat fluxes while decreasing sensible heat fluxes, there is an increase in low clouds associated with increased evaporation. The increased reflection of downward solar radiation from these clouds is the dominant factor driving the global cooling found here*".

Eiseltová *et. al.* (2012) consider:

> *In landscapes with water - abundant aquatic ecosystems, wetlands and soils with high water retention capacity - about 80 % of incoming solar energy is stored as latent heat of water vapour via evapotranspiration, whilst in de-watered landscapes (with a low-water retention capacity) the vast majority of solar energy is transformed into sensible heat.*

Deo (2011) considers:

> *The principle of energy conservation requires that the decrease in evaporative cooling (latent heat) be compensated by an increase in convective heating (sensible heat), assuming ground heat flux is negligible. As such, there is a substantial change in partitioning of available solar energy at the land surface from latent heat to sensible heat flux due to deforestation. Deo et al. (2009) showed that summer-averaged latent heat flux decreased by ~4.8Wm^{-2} while sensible heat increased by ~1.1Wm^{-2} as the surface was modified from a pre-European (native vegetation) to modern day (modified) state. The large reduction in evaporative cooling is consistent with a warmer land surface for modified land cover conditions contributing to a reduction in mean rainfall.*

Lawrence and Chase (2010) consider:

> *... warming was predominantly in response to reduced evapotranspiration and therefore latent heat flux in the current day experiment, with radiative forcing playing a secondary role. The idea that replacing forests with grass and crop lands results in regional warming through reduced evapo-transpiration is not new.*

Models can have completely opposite changes in surface temperature and latent heat flux associated with deforestation, which could be due to problems with some models (i.e. Lawrence and Chase 2010, de Noblet-Ducoudré *et. al.* 2012). Ban-Weiss *et. al.* (2011) caution:

> *In studies of 'realistic' land use and land cover change, it is often difficult to identify what component of climate change may be attributed to changes in latent and sensible heating. Real changes in surface properties would also affect surface albedo and roughness, and it is generally difficult to partition predicted climate change among these causes.*

Pitman *et. al.* (2012) found that many of the temperature indices show locally strong and statistically significant responses to deforestation, noting "*commonly 30–50% of the continental surfaces of the tropics and Northern and Southern Hemispheres are affected statistically significantly*".

From their experiments with 7 coupled atmospheric models de Noblet-Ducoudré *et. al.* (2012) found "*that there is no consistency among the various models regarding how* [land use-land cover change] *affects the partitioning of available energy between latent and sensible heat fluxes at a specific time*". Though for Eurasia and North America de Noblet-Ducoudré *et. al.* (2012) found that "*all models that undergo a change in their forest fraction that is larger than 15% simulate cooler ambient air temperature in all seasons*".

From his modelling of Land Cover Change (LCC) Deo (2011) considered:

> *Such a large shift in energy flux from evaporative cooling to convective heating demonstrates that LCC can exacerbate climate anomalies, such as El Niño events.*
> *...*
> *Since the conversion of native forests into cropping and grazing pastures contribute to an increase in sensible heating, a warmer atmosphere can lead to an increase in the number of hot days. Conversely, the decrease in latent (or evaporative) heating can offset the amount of moisture available for the formation of rain through a reduction in evaporation and transpiration rates. This can produce an increase in the number of dry days. Increases in the number of dry days and more intense heating of the lower atmosphere can lead to more extreme conditions such as droughts and heatwaves ...*
>
> *Second, the reduction in surface roughness, leaf area, and root depth dramatically limits how much water vapor can be recycled into the atmosphere locally through evapotranspiration – an important component of the hydrologic cycle of tropical rainforests ...*

Lawrence and Chase (2010) warn:

> *The robust decreases in evapo-transpiration and regional warming found in the CCSM experiments, and in the supporting field observations and modeling studies, have implications for future land use and the regional impacts of climate change under enhanced atmospheric greenhouse gas concentrations. As the land surface and the hydrological cycle continue to be modified through deforestation, urbanization, agricultural development, further reductions in evapo-transpiration may substantially enhance regional warming on top of projected global warming.*

1.3. Surface Roughness

The structure of vegetation has a significant impact on rainfall that is related to its height, leaf area density, and canopy roughness. Natural vegetation reduces wind speed through its aerodynamically rough, undulating canopy, causing turbulence and the mixing of air. Due to the decrease in wind velocity, the air masses are forced to stack and rise, which is enhanced by the height of the vegetation. This increases the influx of water vapour into the lower atmosphere, and thus promotes condensation and rainfall. As described by Bagley (2011):

> *Depending on whether surface roughness increases or decreases the change enhances or diminishes fluxes of water, energy, and momentum from the earth's surface to the atmospheric boundary layer through the enhancement or diminishment of eddy formation in the surface layer*

Just by their height trees can have an orographic effect (moist air rising over a physical barrier), as noted by Andrich and Imberger (2013) for Western Australia: "*Rainfall changes by ~40 mm for every 100 m in altitude between Fremantle and the hill reservoirs*". Cutting down trees thus reduces the "*surface boundary layer height*" and rainfall.

The decrease in surface roughness caused by deforestation reduces the transfer of energy to the atmosphere in the form of turbulent fluxes and thus rainfall. The low and even canopies of crops and grasslands reduce surface roughness, turbulent mixing in the boundary layer, evapotranspiration and thus rainfall. This is considered by many researchers to be a key contribution to the decrease in rainfall resultant from land cover change (Sud and Smith 1985, Shukla *et. al.* 1990, Nobre *et. al* 1991, Meher-Homji 1991, Claussen 1998, Sud *et. al.* 1998, Hoffmann and Jackson 2000, Foley *et. al.* 2003b, Pitman *et.al.* 2004, Sheil and Murdiyarso 2009, Findell *et. al.* 2007, Chapin III *et al*., 2008, Sheil and Murdiyarso 2009, Findell *et. al.* 2009, McAlpine *et. al.* 2009, Davin and de Noblet-Ducoudré 2010, Nair *et. al* 2011, Kala *et. al.* 2011, Deo 2011, Bagley 2011, de Noblet-Ducoudré *et. al.* 2012, Andrich and Imberger 2013, Chen and Dirmeyer 2016).

Sheil and Murdiyarso (2009) state:

> *Forest evaporation benefits from canopy height and roughness, which leads to turbulent airflows. This has been termed the "clothesline effect," as it is the same reason laundry dries more quickly on a line than when laid flat on the ground (Calder 2005). If moisture is sufficient, forest evaporation is constrained principally by solar radiation and weather (Calder et al. 1986, Savenije 2004). Large tropical trees can transpire several hundred litres of water each day (Goldstein et al.1998).*

An example of the aerodynamic effect on local precipitation has been studied in south-west Australia, where rainfall has reduced and river flows around the city of Perth have fallen by around 40% since the mid twentieth century. This decreasing trend has been attributed to deforestation (Adams 2010). The replacement of forests by cropland and pasture has reduced the aerodynamic roughness of the surface. After clearance of the forests, the rainfall occurs further inland and outside of the river catchments around Perth. An analysis of observations and regional model results by Nair et al. (2011) supports these ideas. The loss of the forest has resulted in reduced wintertime rainfall over the areas cleared, which is partly caused by the reduced aerodynamic roughness after conversion of forests to crops. A more heterogeneous pattern of forest and wheat could have helped to reduce the local change in rainfall (Chapin III *et al*., 2008).

Kala *et. al.* (2011) modelled a summer and a winter cold front in south-west WA to assess the impacts of land clearing, and:

> *found that land-cover change results in a decrease in precipitation for both fronts, with a higher decrease for the summer front. The decrease in precipitation is attributed to a decrease in turbulent kinetic energy and moisture flux convergence as well as a increase in*

> *wind speed within the lower boundary layer. The suggested mechanism is that the enhanced vertical mixing under pre-European vegetation cover, with the decrease in wind speeds close to the ground, enhance microphysical processes leading to increased convective precipitation. The higher decrease in precipitation for the summer front is most likely due to enhanced convection during summer.*

From their modelling of Monsoon rains over India, Sud and Smith (1985) concluded that "*the influence of surface roughness change is as important as that of surface albedo change*", identifying that "*small changes in wind magnitude or direction, can produce significant changes in the moisture convergence and rainfall*", and that "*the presence of tall vegetation over India would increase its July rainfall*". From their global modelling review, Sud *et. al.* (1998) considered that they showed "*that the surface roughness significantly influences the atmospheric circulation and precipitation, especially in the tropics, because it directly affects the boundary layer water vapor transport convergence*", concluding that the *"height of the earth's vegetation cover, which is the main determinant of surface roughness, has a large influence on the boundary layer water vapor transport convergence and the rainfall distribution*".

As well as decreasing rainfall, the reduction in surface roughness due to deforestation is considered to have a strong warming influence (Foley *et al*. 2003, Davin and de Noblet-Ducoudré 2010, Deo 2011, Chen and Dirmeyer 2016), Davin and de Noblet-Ducoudré (2010) noting "*reduced surface roughness leads to weaker turbulent exchanges. Since the energy available at the surface cannot be transferred to the atmosphere through turbulent fluxes, the surface tends to warm*"

Chen and Dirmeyer (2016) consider that surface roughness effects usually dominate the direct biogeophysical feedback of deforestation, while other effects play a secondary role, finding:.

> *Grasslands or croplands are aerodynamically smoother than forest and transfer heat less effectively, thus experiencing higher surface temperatures during daytime and lower surface temperatures at night*

Based on comparisons of surface temperature change from forest to open land at paired observation sites, Chen and Dirmeyer (2016) identified that in summer deforestation leads to an observed daytime warming (+2.23±0.94 K) and a cooling effect at night (−2.05±1.02 K), noting "*roughness change exhibits the largest impact (1.96+0.60 K during the day, −1.62+0.61 K at night)*".

Vegetation can also directly strip water from fog and clouds in mountainous areas and along coastal fog zones with significant affects on the water available for the forests, transpiration and streamflows (i.e. Lima 1984, Meher-Homji 1991, Hutley *et. al.* 1997, Foley et. al. 2003b, Sheil and Murdiyarso 2009). Meher-Homji (1991) note:

> *Even a single tree or a group of trees can trap a substantial quantity of rainwater through the process called horizontal precipitation .... The amount so trapped can vary from 7 to 18% of the rainy-season precipitation and up to 100% of dry-season rains .... The destruction of such cloud forests (as in the Western Ghats of India) can diminish stream flows and ground-water recharge.*

Hutley *et. al.* (1997) identify that numerous observers have considered that the occurrence of low cloud, fog and mist may be important to the survival of Australian rainforests at upland sites. They assessed a rainforest site on the Great Dividing Range west of Brisbane, finding that leaves were wet for 25% of the time solely from dew and fog events, with frequent wetting of the canopy reducing transpiration rates, and allowing the leaves to directly absorb liquid surface water. Hutley *et. al.* (1997) conclude:

> *Fog deposition to the forest provides the equivalent of an additional 40% of rainfall to the site as measured using a conventional rain gauge. A frequently wet canopy results in reduced transpiration rates and direct foliar absorption of moisture alleviates water deficits of the upper crown leaves and branches during the dry season. These features of this vegetation type may enable long-term survival at what could be considered to be a marginal rainforest site.*
>
> *...*
>
> *Near-coastal massifs, such as the Great Dividing Range in southern Queensland, will have an ability to intercept and deflect moist air, which will have a significant local impact on rainfall. The present study has demonstrated the importance of fog and cloud occurrence. This could also be true of upland sites along the entire Eastern Highlands of Australia and may be significant given the frequency of the occurrence of water deficits in Australian rainforests.*

1.4. Aerosols

Aerosols are minute particles suspended in the atmosphere, some of which fulfil an essential role in the hydrological cycle. Aerosols can originate directly from volcanoes, dust storms, sea spray, natural ecosystems, wildfires (including controlled burning), biofuel burning and fossil fuel burning, and a range of other sources, and indirectly via secondary reactions of plant compounds.

By volume, mineral dust and sea-salt are by far the most common aerosols, with significant amounts (in descending order) of sulfates, industrial dust, secondary organic, nitrates, primary biogenic, and soot (Posfai and Buseck 2010), though it is the biological emissions of our seas and vegetation that are primarily responsible for our rainfall.

Aerosols can directly affect the climate by scattering and/or absorbing solar and thermal radiation, or indirectly by acting as cloud condensation nuclei (CCN) and ice nuclei (IN). The chemical composition of the aerosols determine their climatic impact, some reflect solar energy (i.e. sulfates and organics), some strongly absorb solar energy (i.e. black carbon, iron oxide, some organic acids), and some (i.e. sulfate, nitrate and soluble organics) form cloud droplets. Research suggests that aerosol effects are of comparable importance to greenhouse gases as a driver of recent climate trends in the Southern Hemisphere, including Australia (Rotstayn *et. al.* 2008).

Ecological processes have evolved over millions of years and so are complex and multi-dimensional. Having evolved mechanisms to attract atmospheric moisture to them, trees then need to make it rain. Makarieva and Gorshkov (2010) describe the basic physical process: "*most moisture precipitates in the acceptor region where the moist air ascends and vapour condenses, with spatial fluctuations of this process dictated by local turbulent eddies*", though the condensation is largely due to the plants themselves.

Aerosols act as cloud condensation nuclei (CCN) for the formation of clouds, without them cloud droplets cannot form and rain cannot fall. CCN are key elements of the hydrological cycle and climate on regional as well as global scales

Vertical air motions (updrafts), or the mixing of air masses with different temperatures and moisture contents, can lead to the super saturations necessary for cloud formation.. Once CNN have activated the formation of cloud droplets, their continued growth occurs by the deposition of water vapour for as long as water supersaturation is maintained by persisting vertical motion. Water droplets grow by colliding and merging to create larger droplets. The types and quantities of aerosols affect water droplet size and abundance, reflection of solar radiation, and precipitation efficiency. The resultant clouds cover about 60% of the earth's surface and themselves cool the Earth's atmosphere system, as well as precipitating rainfall.

The presence of ice particles in clouds is also a major factor in the formation of precipitation, particularly at lower temperatures. Ice nucleation is the primary process of ice generation. As with water droplets, both inorganic and organic particles have been identified as nucleation agents. Freezing of water occurs at –36 to –38^{o}C. Soot, mineral dust, volcanic ash, and pollen have been found to be potentially important ice nuclei below about -15^{o}C, and fungal spores below about -30^{o}C (Murray *et. al.* 2012), though various bacteria occurring on plants have been found to act as ice nucleation agents at temperatures below -2^{o}C (Lindow *et. al.* 1978, Möhler *et. al.* 2007, Murray *et. al.* 2012. Hill *et. al.* 2014). While it has been postulated that bacteria may be a significant factor in atmospheric ice nucleation, and thus rainfall, Murray *et. al.* (2012) note that "*it is still under debate if there are sufficient bacteria in the atmosphere to have a significant impact*".

Once ice crystals form, the lower vapour pressure of ice favours a transfer of water mass from water droplets to the ice particles, enabling them to grow, they also collect droplets as they fall by collisions with water droplets that freeze on impact.

Aerosols that scatter sunlight reduce the energy flux at the surface of Earth and those that absorb solar radiation cause a warming of the atmosphere but a cooling of Earth’s surface. Overall, such aerosols are thought to have resulted in a cooling effect on the earth's surface and counteracted some of the warming due to increasing atmospheric CO^2 (Ramanathan and Carmichael 2008, Posfai and Buseck 2010).

The abundance of anthropogenic aerosol pollutants from cars, planes, factories and fires are generally considered to dramatically increase CCN concentrations, thereby reducing the size of cloud droplets so that they tend not to coalesce to form the large drops and fall as rain, thus increasing cloud albedo, reflection of sunlight, extending the life of clouds and reducing rainfall (Roberts *et. al.* 2003, Lohmann and Feichter 2005, Rotstayn *et. al.* 2008, Ramanathan and Carmichael 2008, Gunthe et. al. 2009, Posfai and Buseck 2010, Ackerley *et. al.* 2011, Tavares 2012, Pöhlker *et. al.* 2016), though this can vary with different cloud types, and whether pollutants enhance or suppress rainfall remains a contentious issue (Rotstayn *et. al.* 2008, Gunthe *et. al.* 2009). For a cloud with a given water content, an increase in the number of aerosol particles results in a proportional increase in droplet number and a decrease in droplet size, producing an increase in cloud albedo (Twomey 1977). Because small droplets are less likely to precipitate than large ones, the lifetime of clouds is extended (Albrecht 1989).

1.4.1. Biogenic Aerosols

Emissions from the ocean and from terrestrial vegetation are the main biogenic aerosol sources. Sea-salt particles arise through the bursting of bubbles that rise to the sea surface. The surface microlayer of the ocean is enriched in microorganisms, viruses, and extracellular biogenic material which can enter the atmosphere by bubble bursting, with sea-salt particles comprised of around 10% organic matter (Posfai and Buseck 2010).

Vegetation can release primary aerosol particles and generate secondary biological aerosol particles. Under natural conditions biogenic aerosol emissions provide most of the cloud condensation nuclei and are thus responsible for most rainfall. For example, in the Amazon, outside the burning season, Whitehead *et. al.* (2016) found that organic material contributed around 81% of the total mass of aerosols, with the balance of non-biological particles largely consisting of advected Saharan dust and sea salt from the Atlantic. Obviously closer to the coast marine aerosols become more significant.

Natural terrestrial primary aerosols can include significant organic matter, particularly of pollen, fungi and plant spores, leaf fragments, and bacteria (Möhler *et. al.* 2007, Tavares 2012, Whitehead *et. al.* 2016). Whitehead *et. al.* (2016) found that in the Amazon primary biological aerosols were dominated (around 70%) by fungal spores. Biogenic aerosols occur at relatively low densities and so are capable of attracting a great deal of water vapour and forming large, heavy droplets that rapidly precipitate. Emissions can total about half a ton per ha/year (Tavares 2012). A high proportion of natural aerosol particles act as CCNs, about 60 to 80 percent in the Amazon (Tavares 2012).

Volatile organic compounds (such as terpenes and isoprene) emitted from vegetation can oxidize in the atmosphere to form secondary organic aerosols that are CCN. It may be that these are "*the major and least studied aerosol source in Australia*" (Rotstayn *et. al.* 2008). Scott *et. al.* (2014) estimate that secondary organic aerosols increase the global annual mean concentration of cloud condensation nuclei by 3.6–21.1% and global annual mean cloud droplet number concentration by 1.9–5.2%, with increases being most significant over forested regions.

Volatile organic compounds (VOCs) are organic compounds that readily diffuse into the air. They include both human-made and naturally occurring chemical compounds. The majority of biologically generated VOCs are produced by plants, such as plant scents and the blue haze characteristic of eucalypt forests. Not only do they play an important role in communication between plants, and messages from plants to animals, but also between plants and moisture-laden air.

Trees, in particular, are efficient emitters of volatile organic compounds (VOC) that react with atmospheric oxidants to form aerosols that serve as CCN (cloud condensation nuclei). Studies in the pristine Amazon rainforest showed that fine particles (which account for most of the cloud condensation nuclei) consist mostly of secondary organic material derived from oxidized biogenic gases (Whitehead *et. al.* 2016).

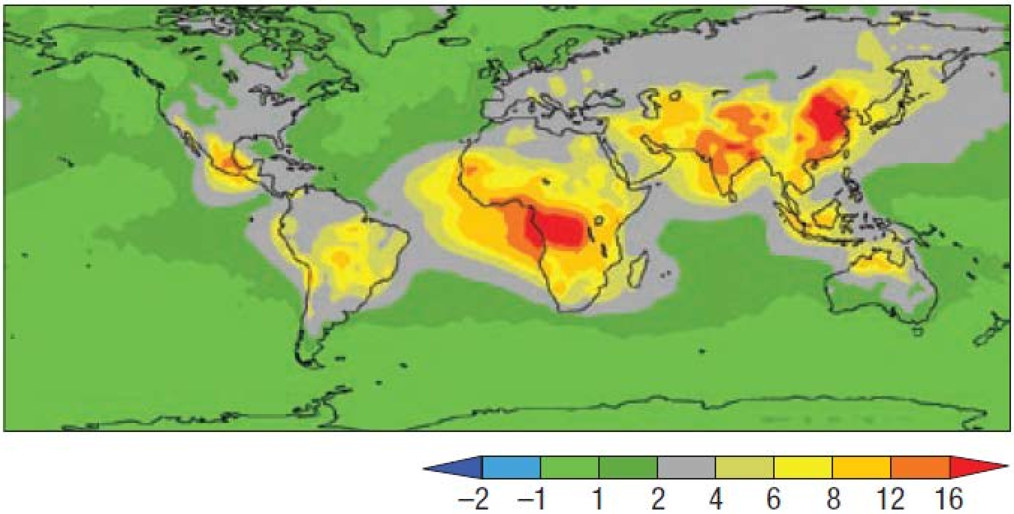
Eucalypt forests appear to be particularly efficient at producing VOC that develop into secondary aerosols. Suni *et. al.* (2008) found that the eucalypt forest they studied was a very strong source of new aerosol particles with formation events taking place on 52% of the days, which is 1.9 to 3.4 times as often as found in Nordic field stations. They also found that in summer and autumn nocturnal production was the major mechanism for aerosol formation.

1.4.2. Soot Aerosols

Soot is the strongest absorber of solar radiation among all major aerosols (Posfai and Buseck 2010). Globally, the annual emissions of soot (black carbon) are (for the year 1996) ~8 Tg yr^{-1}, with about 20% from biofuels, 40% from fossil fuels and 40% from open biomass burning (Ramanathan and Carmichael 2008). Biomass burning produces atmospheric particles in amounts that affect both the regional and global climate (Posfai and Buseck 2010, Ackerley *et. al.* 2011).

Soot mixes with sulphates, nitrates, organics, dust and sea salt to form 'atmospheric brown clouds'. Their concentrations peak close to major source regions and give rise to regional hotspots of soot-induced atmospheric solar heating.

From their study of atmospheric brown clouds over the Indian Ocean and Asia, Ramanathan *et. al.* (2007) found that atmospheric brown clouds resulted in a tenfold increase in airborne soot and other aerosol particles that enhanced lower atmospheric solar heating by about 50 per cent, with 90% of this increase attributable to soot, concluding "*that atmospheric brown clouds contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends*".



Atmospheric solar heating due to soot from the study by Chung *et al*. for the 2001 to 2003 period. From Ramanathan and Carmichael (2008).

Ramanathan and Carmichael (2008) identify that in those regional hotspots experiencing 50% atmospheric solar heating there was a corresponding surface cooling (dimming) of 5 to 10%. In relation to the redistribution of solar warming from the surface to the atmosphere, Ramanathan and Carmichael (2008) comment "*globally, this redistribution can weaken the radiative–convective coupling of the atmosphere and decrease global mean evaporation and rainfall*"

Ramanathan and Carmichael (2008) consider that soot's climate change forcing is as important as greenhouse gasses in the observed retreat of over two thirds of the Himalayan glaciers. They also identify that the deposition of soot over snow and sea ice may have resulted in an Arctic surface warming trend of as much as 0.5 to 1°C due to surface darkening, and that soot has caused changes in South Asia's monsoons because of reduced evaporation (surface cooling) and weakened monsoonal circulation (reduced sea surface temperature differentials).

The increased aerosols generated by smoke and anthropogenic sulfate aerosols can depress rainfall by reducing the size of cloud droplets, allowing the clouds to travel further from their origin (Lohmann and Feichter 2005, Ramanathan and Carmichael 2008, Ackerley *et. al.* 2011, Tavares 2012). Smoke also increases the number of “black carbon” aerosols that absorb solar energy, increasing atmospheric heat which can cause cloud droplets to evaporate before precipitating, thus intensifying the rainfall suppression (Ramanathan and Carmichael 2008, Tavares 2012). Roberts *et. al.* (2003) considered their "*modeling studies suggests that absorption of sunlight due to smoke aerosol may compensate for about half of the maximum aerosol effect*".

Ackerley *et. al.* (2011) also identify that sulfate aerosol particles can act directly on climate by scattering or absorbing radiation, and by changing the albedo of clouds making them more or less reflective. From their modelling Ackerley et. al. (2011) concluded that increases in aerosol loading cause a reduction in rainfall, finding for the drought stricken Sahel in central Africa "*that historical SO^2 emissions are likely to explain most of the 1940–80 rainfall changes and a significant proportion of the more pronounced 1950–80 drying*".

Soot is removed from the atmosphere by rain and snowfall and is considered to have an atmospheric lifetime of about one week, though its atmospheric longevity can be extended where it suppresses rainfall.

Biomass burning is one of the main sources for carbonaceous aerosol in the atmosphere, globally contributing about 40% of CO^2, 32% of CO, 38% of tropospheric ozone, 7% of total particulate matter and 39% of particulate organic carbon (Dentener *et. al.* 2006). Bushfires inject large volumes of particulate matter into the Australian atmosphere every year, contributing around 5% of the worlds annual emissions (Rotstayn *et. al.* 2008).

In the Amazonian rainforest widespread biomass burning in the dry season can result in a substantially increased aerosol optical depth over large areas of Amazonia, as well as modified cloud properties and suppressed precipitation (Roberts *et. al.* 2003, Whitehead *et. al.* 2016)

Nothing in nature is ever simple. Graf *et. al.* (2007) investigated the effects of aerosols from the 1997 Indonesian fires, finding *" although the monthly mean rainfall is depressed over most of the heavily polluted areas, there are coherent areas, which are also polluted, where the opposite is the case. ... mainly over or in proximity to the sea, where moisture supply is high".*

Rotstayn *et. al.* (2008) consider that Asian anthropogenic aerosols, largely generated by forest and peat fires, can affect monsoonal rainfalls in Australia. They hypothesise that aerosols cool the Asian continent and surrounding oceans, increasing the temperature gradient and monsoonal winds between Asia and Australia, which bring increased rainfall to northern Australia. Without this effect north-west Australia could expect declining summer rainfall in response to climate change.

Rotstayn *et. al.* (2008) consider "*that aerosol effects are of comparable importance to greenhouse gases as a driver of recent climate trends in the Southern Hemisphere, including Australia*".

Ramanathan and Carmichael (2008) consider in relation to Black Carbon (soot):

> *Given that BC has a significant contribution to global radiative forcing, and a much shorter lifetime compared with CO2 (which has a lifetime of 100 years or more), a major focus on decreasing BC emissions offers an opportunity to mitigate the effects of global warming trends in the short term .... Reductions in BC are also warranted from considerations of regional climate change and human health*
>
> *... the elimination of present day [atmospheric brown clouds] ABCs through emission reduction strategies would intensify surface warming by about 0.4 to 2.4 ºC... If on the other hand, the immediate target for control shifts entirely to BC (owing to its health impacts) without a reduction in non-BC aerosols, the elimination of the positive forcing by BC will decrease both the global warming and the retreat of sea ice and glaciers. It is important to emphasize that BC reduction can only help delay and not prevent unprecedented climate changes due to CO^2 emissions.*

1.4.3. Dust Aerosols

Desert dust can be the dominant particle type even thousands of kilometers from the source. In addition to its direct and indirect climate effects, atmospheric dust plays an important role in the global biogeochemical cycle of iron, a limiting nutrient in many oceanic ecosystems (Posfai and Buseck 2010). Australia contributes more than 70% of the atmospheric dust loading over most of the Southern Hemisphere (Rotstayn *et. al.* 2008). Posfai and Buseck (2010) suggest *"that mineral dust is a potential cleansing agent for organic pollutants".* Dust generation is episodic, mostly related to droughts. When dust is blown out to sea to the north-east or north-west it can potentially affect cyclone activity in the Australian region, and when blown to the southern ocean the iron-rich dusts stimulate phytoplankton growth (Rotstayn *et. al.* 2008).

1.5. Soil Moisture

Recycling of rainfall back into the atmosphere as water vapour by evapotranspiration is one of the most important land–atmosphere interactions in the climate system. While evaporation from water, land and vegetation surfaces makes a significant contribution to water recycling, it is transpiration of soil moisture by vegetation that is most significant. Thus the availability and accessibility of soil moisture are key drivers of the hydrological system. Any increase in runoff implies a decrease in water available for recycling by evapotranspiration.

When rain falls some is intercepted by ground and vegetation surfaces where it can be rapidly evaporated back into the atmosphere, and some is rapidly transported by overland flow directly into streams, though most is captured as soil moisture or groundwater where its movement is slowed. Once in the soil it is available to plants for transpiration, until it seeps into streams or deep aquifers out of reach.

Soil moisture and groundwater are essential for slowing down and evening out the water cycle, extending the accessibility of water for plants over weeks, months and years. A wet episode can influence groundwater contribution to summer evaporation for several years afterwards. For their study area, Lam *et. al.* (2011) consider the time scale to transport water tens of kilometers in the subsurface is a minimum of tens of years, and at maximum tens of thousands of years, compared to atmospheric processes that can take hours.

Soil moisture can directly affect rainfall through evapotranspiration (Guo *et. al*. 2006, Lam *et. al.* 2007). Lam *et. al.* (2007) found "*In a surprisingly large part of the land surface, soil moisture influence on precipitation occurrence is of the same order of magnitude as the influence of the annual cycle*". Guo *et. al.* (2006) examined the impacts of soil moisture conditions on rainfall generation for the boreal summer season using a range of models, concluding that soil moisture has a significantly strong impact on rainfall in the "*transition zones between dry and wet areas, where evapotranspiration variations are suitably high but are still sensitive to soil moisture*". In dry areas evapotranspiration rates "*are sensitive to soil moisture, but the typical variations are generally too small to affect rainfall generation*".

Deforestation can have a significant effect on the water-cycle by increasing surface run-off (thereby reducing the water available to replenish soil reserves), by changing deep rooted vegetation to shallow-rooted vegetation (thereby reducing the accessible volume of soil moisture), and altering watertables. This means that less water is available for recycling by transpiration, particularly in dry periods.

Sheil and Murdiyarso (2009) state:

> *Water reserves are important. Plants with high stem volumes allow transpiration to outstrip root uptake, as stem water reserves are depleted by day and replenished at night (Goldstein et al. 1998, Sheil 2003). Trees (and forest lianas) typically have deeper roots than other vegetation and can thus access subterranean moisture during droughts (Calder et al. 1986, Nepstad et al. 1994). Many forest soils possess good water infiltration and storage—properties often lost with deforestation (Bruijnzeel 2004). Vertical translocation of soil water through the forest soil profile by roots at night may also be important (Lee et al. 2005).*

Rahgozar *et. al.* (2012) undertook a comparison of the water budgets of grasslands and forests in Florida, finding that annual totals of evapotranspiration averaged 850mm for grassland and 1100mm for the alluvial wetland forest, and that grasslands intercepted less rainfall, had higher runoff, lower infiltration, and higher watertables.

Von Randow *et. al.* (2004) undertook comparisons of soil moisture down to 3.6m in Amazonian pasture and rainforest, finding similar use of soil moisture in the top 2m of the soil profile, with rainforest using more moisture towards the end of the dry season and less in the wet season. Below 2m depth the pasture had little effect on soil moisture, whereas the rainforest made substantial use of deep soil moisture during the dry season. von Randow *et. al.* (2004) comments:

> *The pasture vegetation withdraws water only from the upper layers of the soil with the water stored in the layer from 2 to 3.4m deep showing only little variation, mainly caused by drainage. In the forest, on the other hand, the soil water storage changes more rapidly in this layer – the seasonal change was about 290mm in the forest and 110mm in the pasture.*

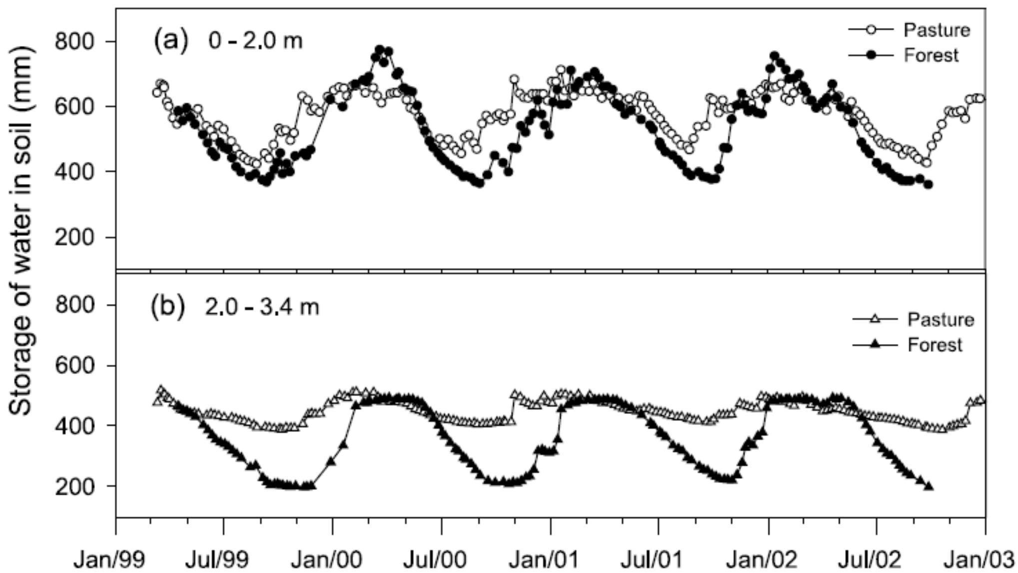


Fig. 5 from von Randow *et. al.* (2004): Storage of water in the soil at forest and pasture sites, for the layers from (a) 0–2m and (b) 2–3.4m deep

In their Western Australian study, Nair *et. al.* (2011) found that transpiration from the native vegetation is less sensitive to soil moisture availability than nearby croplands, observing:

> *The deep rooted native vegetation has access to the underground aquifer whereas the shallow rooted agricultural crops are reliant on near-surface soil moisture and hence their greater sensitivity to soil moisture. One of the consequences of replacing native vegetation with agricultural crops is the removal of this link between the underground aquifer and the atmosphere.*

1.5.1. Runoff

Australia's low and highly variable rainfall pattern, and the use of most rainfall by vegetation, means that we have one of the lowest amounts of runoff to rivers and deep drainage to groundwater in the world. Native vegetation in semi-arid Australia is dominated by trees or woody shrubs with relatively deep roots that is effective at taking full advantage of any available water, using most of the rainfall in ways that minimize the amount of water that leaks past the root zone. (Williams *et. al*. 2002)

The evidence is that by reducing rainfall interception by vegetation, reducing evapotranspiration and changing soil properties, deforestation generally results in an increase in runoff to streams (Bosch and Hewlett 1982, Williams *et. al*. 2002, Silberstein *et. al.* 2003, Bari and Ruprecht 2003, Brown *et. al.* 2005, Bagley 2011). The increased runoff can result from changes in surface runoff or changes in baseflow. Surface runoff increases where the infiltration ability of the soil is reduced (such as by compaction), when the effectiveness of surface vegetation and leaf litter to slow overland flows is reduced (providing less time for infiltration), or when raised watertables reduce the storage capacity of the soil.

Silberstein *et. al.* (2003) and Findell *et. al.* (2007) identify that when the watertable comes too close to the surface that there is an increase in saturated areas, and a reduced maximum water holding capacity of the remaining unsaturated soils, and hence an increase in surface runoff, and potentially flooding, leaving less moisture available for evapotranspiration.

Williams *et. al*. (2002) consider that in Australia large scale clearing of native vegetation and its replacement with annual crops and pastures have substantially increased the amount of water leaking beneath the root zone and entering the internal drainage and groundwater systems of the landscape.

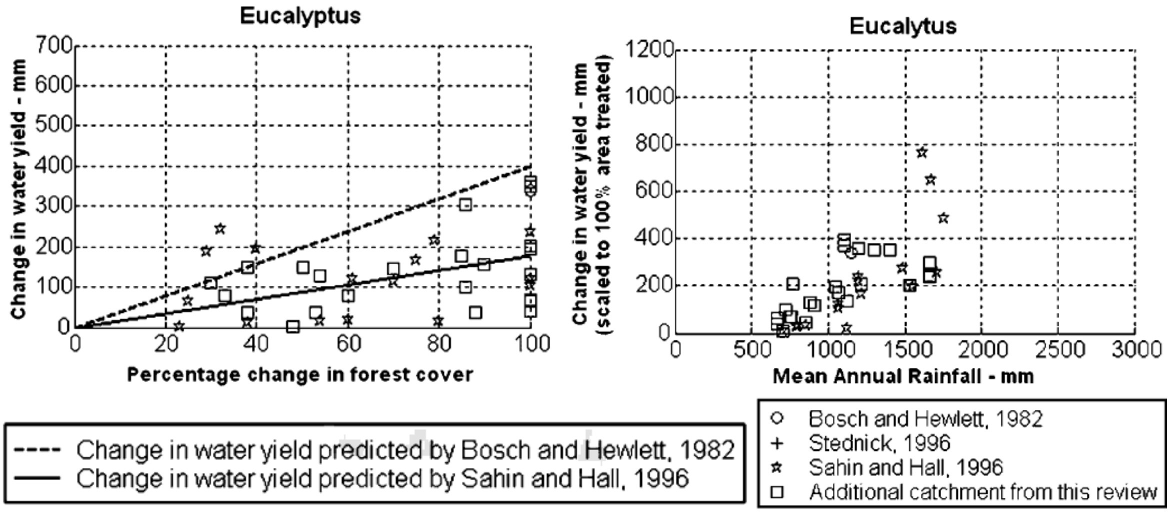
Ruprecht and Schofield (1991a, b) partially deforested (western 53% of the catchment) a small (344ha) experimental catchment in southwest Western Australia in 1976 to study the effects of agricultural development on water quantity and quality, finding:

> *The impact on the groundwater system in the cleared area was dramatic. Initial rates of rise were only 0.11 m year^{-1} but this increased after 10 years to average 2.3 m year^{-1}. Groundwater rises of 15 m in the valley and 20–25 m on the lower sideslopes were observed over 13 years. A small seep (groundwater discharge area) appeared for the first time in 1988 and by 1989 it covered an area of 1 ha. Streamflow initially increased by 30 mm year^{-1} (4.0% rainfall) compared with a native forest average streamflow of 8 mm year^{-1} (1.0% rainfall). However, since the seep area developed, the increase in streamflow has been 50 mm year^{-1} (6.6% rainfall).*

Ruprecht and Schofield (1991b) report on subcatchments in an area of 300ha subject to partial clearing noting:

> *Within subcatchments that were 60–70% cleared, groundwater level rises were observed of 7.8–10.2 m compared with a 5.8 m rise with 32% clearing and a 2.3 m fall in a native forest control, from 1977 to 1989. The combination of clearing treatments affecting 38% of the catchment has resulted in a modest (13 mm) increase in catchment streamflow. This was over double the average forested streamflow.*

From their review, Bosch and Hewlett (1982) concluded that for each 10% reduction in eucalypt cover there is an increase of around 40mm in annual water yield. From their review of paired catchments, Brown *et. al.* (2005) found that all studies identified similar trends for eucalypt forests, pine forests, hardwood and scrub, with variable magnitudes of runoff increases. Runoff increased in line with the percentage cleared, though for any impact of vegetation change to be detected at least 20% of the catchment needed to be treated. Changes in runoff also increased in line with rainfall.



Extracts of Figs. 1 and 2 from Brown et. al. (2005): Water yield changes as a result of (LEFT) changes in vegetation cover and (RIGHT) as a function of mean annual rainfall (from Bosch and Hewlett (1982), Sahin and Hall (1996) and Stednick (1996)).

Bagley (2011) consider that in the tropics deforestation increases surface runoff, which alters river flow, noting "*Since 1970 the Araguaia River in east-central Brazil has experience a 25% increase in discharge, with recent modeling efforts suggesting that deforestation in the region was responsible for nearly 2/3 of the increase*".

Studies in experimental catchments in the south–west of Western Australia examined the impacts of clearing for agricultural development on water yields to streams (Bari and Ruprecht 2003), finding that clearing led to permanent increases of water yield of about 30% of annual rainfall for high rainfall areas (1100 mm mean annual rainfall) and 20% of annual rainfall for low rainfall areas (900 mm annual rainfall).

All else being equal, water that is lost from a catchment as runoff is no longer available for recycling by evapotranspiration, so deforestation or modification of vegetation that results in an increase in runoff is effectively reducing atmospheric moisture by a corresponding amount.

While the evidence is that permanent clearing of native vegetation results in an increase in runoff to streams, which can largely be attributed to a reduction in evapotranspiration, it is equally clear that activities such as logging and thinning can result in reduced runoff over time. The generalised pattern following heavy and extensive logging of an oldgrowth forest is for there to be an initial increase in runoff peaking after 1 or 2 years and persisting for a few years. Water yields then begin to decline below that of the oldgrowth as the regrowth uses more water. Water yields are likely to reach a minimum after 2 or 3 decades before slowly increasing towards pre-logging levels in line with forest maturity. (Kuzcera 1987, Vertessy *et. al.* 1998, Cornish and Vertessy 2001, Bari and Ruprecht 2003, Brown *et. al.* 2005, Burrows *et. al.* 2011).

This is explored in more detail in Section 2.4 of this review.

1.5.2. Rooting Depth

Roots provide the basis for plant growth, providing access to both water and nutrients. Along with litter fall, roots are the primary input of organic carbon into the soil, with below ground carbon storage more than twice aboveground storage (Jackson *et. al.* 1996) . Below ground primary production is often 60-80% of total net primary production (Jackson *et. al.* 1996).

Evaporation is only effective for water at or near the earth's surface, whereas plant roots are able to tap into soil moisture and groundwater deep below the surface and recycle the water into the atmosphere by transpiration. The process of evaporation can access surface soil moisture, varying with soil type and structure, through diffusion (the movement of water along a concentration gradient from wet soils to dry). The evaporative “extinction depth” is the depth below which no further movement of water towards the surface occurs via diffusion. For bare sandy soils the extinction depth has variously been identified as 50-100cm (Mughal *et. al.* 2015).

The roots of plants allow access to water at greater depths depending on their rooting depth. The deeper the roots go, the larger volume of soil moisture that can be accessed. Soil mycorrhiza and diffusion allow access to moisture deeper than the root zone.

Zang *et. al.* (2001) note "*studies indicate that deep roots play an important* hydrological role *in plant systems, especially under dry conditions ... As the soil progressively dries, more water is extracted from deeper layers to keep stomata open. As a result, trees are able to maintain a relatively constant evapotranspiration rate over time, even when soil moisture in the upper part of the soil is limited. Under such conditions, shallow-rooted plants tend to close their stomata and have a reduced evapotranspiration rate. In regions with dry climates, plant-available water capacity is expected to be a main reason for differences in annual evapotranspiration between trees and shallow-rooted plants".*

Most roots are near the surface and diminish in volume with depth. Root depth can be limited by physical barriers or adverse soil conditions. Roots can find ways through barriers to extend to greater depths, and often extend down to water tables. Stone and Kalisz (1991) identify that roots near a water table may be more effective in absorption by 1000 times or more than those in drier soil above.

Jackson *et. al.* (1996) found that tundra, boreal forest, and temperate grasslands have the shallowest rooting profiles, with 83-93% of roots occurring in the top 30cm of soil, compared to deserts and temperate coniferous forests showed the deepest rooting profiles, with only 50% of roots in the uppermost 30 cm. Root biomass also varied greatly from forests and sclerophyllus shrublands with a maximum of 5kg m^{-3} (rainforests with densities of over 40 kg m^{-3} in the shallowest depths) down to croplands, deserts, tundra and grasslands, all of which had a root biomass <1.5 kg m^{-3}. (with never more than 5kg m^{-3} in the most densely rooted cases).

Eamus *et. al.* (2002) found savanna eucalypts had a root biomass up to 12.83 kg m^{-3}. Eamus *et. al.* (2002) excavated down to 2m, finding 77-90% of total root biomass in the upper 0.5 m of soil, with about 5 % in the next 0.5 m and 5-15 % in the 1- 2 m depth range, noting:

> *The rapid decline of biomass with depth was because of the steep decline in coarse root biomass rather than fine roots which were more evenly distributed with depth. Such a distribution of fine roots is required if, as calculated by Cook et al. (1998), water must be extracted from the entire upper 6-8 m of soil to account for the observed rate of canopy water use in the dry season. Therefore fine root biomass should be significant at depth.*

In their literature review relating to root depth, Stone and Kalisz (1991) identify a range of recorded maximum root depths for various eucalypt species from 1.5-60m. Of the 22 recorded depths, 9 were 15m or more, with the maximum depths given as 40m, 45m,and 60m. They also report root depths of 10m for 15m high Eucalyptus signata forest and 18m for <8m high Mallee.

Jackson *et. al.* (1996) identify that roots of one species have been recorded extending down 50m. Lima (1984) notes claims of eucalypt root penetration of up to 18m and well over 30 m, and that some eucalypt species are characterized by developing shallow root systems, whereas some species have inherently deep-going main roots.

One of the key problems in identifying the importance of deep roots is that most root studies are limited to <1m depth, and very few extend to >2m depth, so there is a paucity of information on the depths to which roots go (Lima 1984, Stone and Kalisz 1991).

Many researchers have identified the reduction in vegetation rooting depth caused by deforestation as having a key role in reducing rainfall (i.e. Nobre *et. al* 1991, Hoffmann and Jackson 2000, Foley *et. al.* 2003, Findell *et. al.* 2007, Findell *et. al.* 2009, Lawrence and Chace 2010, Bagley 2011, Jasechko *et. al*. 2013). Bagley (2011) found that deforestation dried the soil during drier periods, concluding "*the replacement of tropical forest with shrubby grasses removed the ability of vegetation to access moisture in deeper soil levels, forcing the vegetation to pull more moisture from top soil layers and less from lower layers*".

The reduction in vegetation rooting depth is also considered to have a significant effect of energy flows because the reduced transpiration means less conversion of energy to latent heat and thus increased ground temperatures (*von Randow, et al.*, 2004, Findell *et. al.* 2007, Findell *et. al.* 2009, Bagley 2011), as noted by Bagley (2011):

> *in the case of tropical deforestation shallow grasses and shrubs commonly replace large leafy trees with long roots capable of reaching water deep in the soil (Culf et al., 1996; Davin and de Noblet-Ducoudré, 2010). The grasses are incapable of releasing the same amount of energy and moisture in the form of latent heat flux as the trees. As a result, evaporative cooling decreases, the local temperature increases, and sensible and radiative fluxes rise.*

2. THE DRYING OF AUSTRALIA

It is apparent that the arrival of Aboriginal people some 50,000 years ago led to changes to the vegetation of Australia by their use of fire as a land management tool. It has been suggested that these changes caused a reduction in woody vegetation and an increase in grasslands of sufficient magnitude to cause a drying of large areas of the continent, and increasing aridity, such as in central and north-west Australia.

The more recent arrival of Europeans initiated widespread clearing in the better watered areas, as well as extensive vegetation modification through logging and grazing. Around 15% of the Australian continent has been cleared of native vegetation, including 22% of forests and woodlands, and some 48% of the continent comprises native vegetation used for grazing and logging. These massive changes have had major ramifications for the climates in the regions most affected.

Rainfall is declining in southern and eastern Australia, as temperatures are rising. . Rainfall has been declining seasonally in the most heavily cleared areas, with abrupt reductions in the 1970s in south-western Australia and eastern Queensland. Autumn rainfall over Victoria declined by about 40% over 1950–2006. From the mid-1990s to late 2000s, many Australian regions were plagued by concurrent severe droughts, which later became known as the Millennium Drought, the most severe in recorded history.

Deforestation has significantly contributed to these climatic trends by reducing transpiration by vegetation, reducing the ability of vegetation to attract moist air, reducing the ability of tall rough vegetation to slow winds and increase rainfalls, reducing the availability of aerosols to act as cloud condensation nuclei, reducing evaporative cooling and cloud cover, and increasing runoff.

The removal of deep rooted forests and woodlands has reduced evapotranspiration and allowed saline ground-waters to rise over large areas of Australia, with 5.7 million hectares currently at risk of dryland salinity. This could rise to over 17 million hectares by 2050. This has turned many of our rivers saline, caused widespread degradation of native ecosystems and agricultural lands, destroyed infrastructure, and diminished biodiversity.

Logging confounds these changes because after some years regrowth trees can increase transpiration and the transfer of soil moisture to the atmosphere. The widespread conversion of oldgrowth forests to regrowth has reduced runoff to streams, and the increased demands of the regrowth seems to be exceeding available soil moisture in some areas, causing significant water stresses in drier catchments and increasing deaths of trees in droughts. The overall impacts on rainfall caused by the conversion of oldgrowth forests to regrowth remain unknown.

It is apparent that climate change due to increasing CO^2 is compounding the impacts of deforestation, and will become the dominate influence into the future, though it may not be primarily responsible for the climatic changes Australia has experienced so far.

2.1. The Early Changes

Significant anthropogenic changes to the Australian climate are likely to have originated with the Aborigines some 50,000 years ago because of their use of fire to manage vegetation.

Considerable attention has focussed on the effects of vegetation changes on the Australian monsoon. Studies have identified a reduction in woody vegetation and increase in grasses is likely to have occurred in central Australia around 50,000 to 40,000 years ago (the late Quaternary) due to Aboriginal burning practices, such vegetation changes are likely to have had significant effects on northern Australia's climate, weakening the continental penetration of the summer monsoon., thereby creating vegetation feedbacks (Johnson et. al. 1999, Bowman 2002, Miller *et. al* 2005, Miller *et. al.* 2007, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013).

Traditional burning practices across northern Australia were undertaken systematically throughout the dry season, in part to promote grasses as feed for kangaroos for hunting. Miller et. al. (2007) note:

> *Fire can be an effective agent of ecosystem change. Humans have had controlled use of fire since the Middle Quaternary. They burn landscapes for many purposes, from clearing passageways and hunting along the fire-front, to signalling distant bands and promoting growth of preferred plants.*

This burning regime has resulted in significant vegetation changes, for example Bowman *et. al.* (2010) observe:

> *Prior to the arrival of people in the Australian–New Guinea region, the fire regime was most probably characterized by infrequent high-intensity fires (Bowman, 2002). Thus prehuman landscapes are likely to have been different from today, with fire-adapted species less abundant, the savanna (mixtures of tropical grass and trees) more geographically restricted, and evergreen dry forests and rain forests more widespread.*

Such a landscape would have been cooler and wetter than today's savanna and desert landscape. Johnson *et. al.* (1999) assessed carbon isotopes in emu eggshells to identify broad vegetation changes in the Lake Eyre basin, leading them to conclude that identified vegetation changes around 40,000-50,0000 years ago were likely to be related to climate changes brought about by Aboriginal burning, concluding:

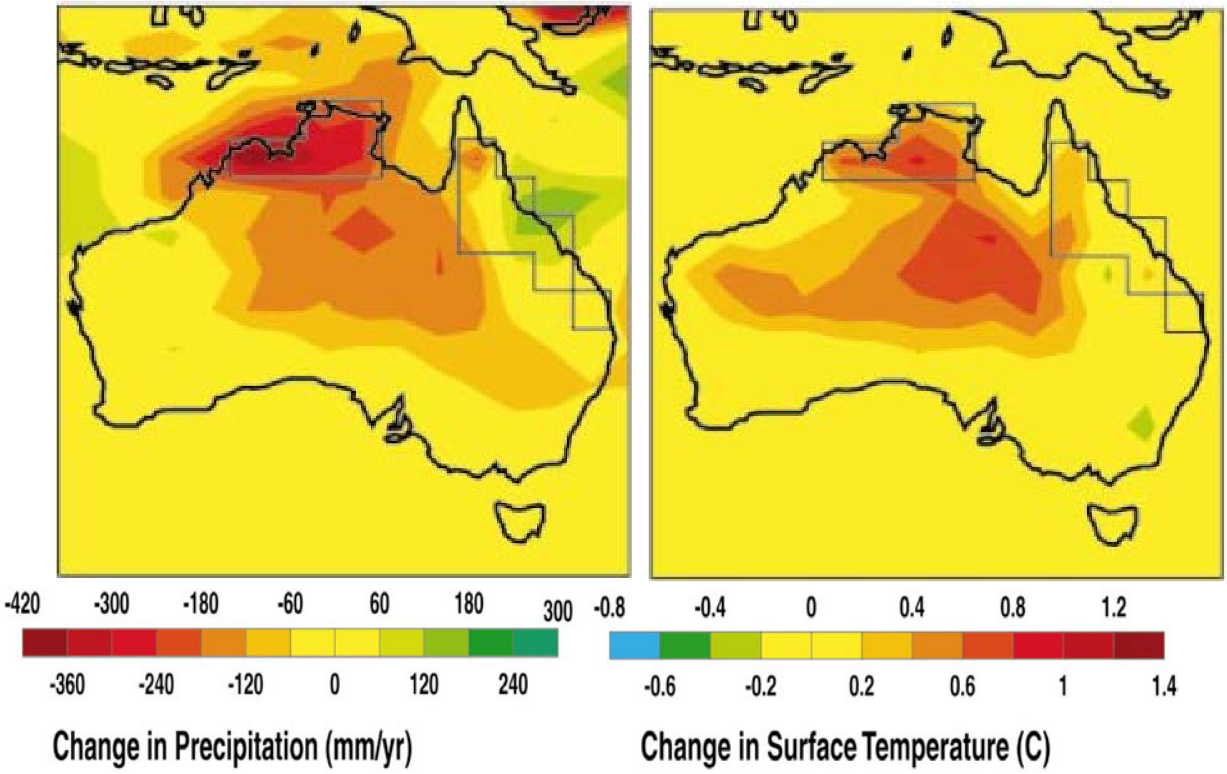
> *The effectiveness of the summer monsoon at Lake Eyre decreased substantially at approximately the same time as megafauna extinction (6) and never fully recovered, A change in vegetation type across northern Australia brought about by the burning practices of the first human colonizers may have reduced this wet season feedback and, consequently, diminished the effectiveness of the summer monsoon at Lake Eyre during the early Holocene*

Hoffmann and Jackson (2000) consider that "*Humans have increased the frequency of fire, primarily in moist tropical savannas where burning now typically occurs at intervals of 1–3 yr ... a rate that can greatly reduce savanna tree densities*". To assess the impact of conversion of savannas to grasslands they modelled changing woody plant cover from 50% to 0% in 5 moist savannas, including northern Australia. Hoffmann and Jackson (2000) found that tree reduction resulted in a significant increase in temperature and decline in precipitation in all savanna regions (except northern Africa). For northern Australian moist savannas they identified declines of 121 mm yr^{-1}

(13%) in precipitation, 70 mm yr^{-1} (9%) in evapotranspiration, 51 mm yr^{-1} (37%) in convergence, and 0.36°C in temperature. Their modelling shows impacts being most severe in the northern territory with impacts extending to encompass central Australia.

Hoffmann and Jackson (2000) conclude:

> *This study indicates that these dry periods may become more frequent following the conversion of savanna to grassland, a change that would have a negative impact on tree regeneration.*
>
> *These proposed negative effects on tree density would exacerbate the direct effects of humans on savanna vegetation. A reduction in precipitation brought about by anthropogenic vegetation change should drive further reductions in tree cover, as well as slow the succession of grassland to savanna. Thus any direct effect of humans on the savanna environment would be accelerated because of climatic feedbacks.*



Change in mean annual precipitation [LEFT] and surface air temperature [RIGHT] resulting from conversion of tropical savanna to grassland. Note the extent of impacts far from changed areas (grey squared outlines). From Hoffmann and Jackson (2000).

Johnson *et. al.* (1999)'s identification of likely climate changes resulting from Aboriginal burning generated considerable interest. A review Bowman (2002) concluded "*this interpretation is difficult to sustain given the great difficulty in extracting a clear 'signal' of an anthropic impact from the inherent variability and fragmentary record of the palaeo–summer monsoon".* Since then a variety of modelling studies have found that the likely magnitude of vegetation changes can significantly affect the pre-Monsoon climate (Miller *et. al.* 2005, Notaro *et. al.* 2011, Wyrwoll *et. al.* 2013)

From their modelling Miller *et. al.* (2005) concluded:

> *Additional simulations show that the penetration of monsoon moisture into the interior is sensitive to biosphere-atmosphere feedbacks linked to vegetation type and soil properties.*

> *This sensitivity offers a resolution to the observed failure of the Australian Monsoon to penetrate the interior in the Holocene. Postulated regular burning practiced by early humans may have converted a tree-shrub-grassland mosaic across the semiarid zone to the modern desert scrub, thereby weakening biospheric feedbacks and resulting in long-term desertification of the continent*

Miller *et. al.* (2007) analysed the eggshells of a large sample of emu shells, shells of the extinct *Genyornis newtoni* and wombat teeth, identifying a nearly continuous record of dietary intake for *emus* throughout the past 140 thousand years and for *Genyornis* before they became extinct around 45-50 thousand years ago. They consider "*Our eggshell and wombat tooth derived* [C3 and C4] *data provide firm evidence for an abrupt ecological shift around the time of human colonization and megafaunal extinction in Australia, between 50 and 45 ka*", which "*suggest a tree/shrub savannah with occasionally rich grasslands was converted abruptly to the modern desert scrub*", stating:

> *We speculate that ecosystem collapse across arid and semi-arid zones was a consequence of systematic burning by early humans. We also suggest that altered climate feedbacks linked to changes in vegetation may have weakened the penetration of monsoon moisture into the continental interior, explaining the failure of the Holocene monsoon. Climate modeling suggests a vegetation shift may reduce monsoon rain in the interior by as much as 50%.*
> *...*
> *The reduction in surface roughness, changed albedo, reduced recycling of rainfall by evapotranspiration, and more rapid runoff, all of which would accompany a transition from a treed-savannah to the modern desert scrubland, may have resulted in a significant weakening of monsoon rain over the Lake Eyre Basin, and even as far south as Port Augusta and the Darling-Murray Lakes throughout the Holocene*

Marshall and Lynch (2008) dismissed the results of Miller *et. al* (2005) on the basis of the "*extreme and idealistic scenarios tested in their study*", concluding from their modelling that:

> *The results of this study suggest that sea level and solar insolation variations over the Australian monsoon region are primarily responsible for the changes in the intensity, southward extent, and timing of the Australian summer monsoon over the last 55,000 years. Vegetation and greenhouse gas radiative forcing perturbations, on the other hand, are responsible for only small proportions of the variation in the simulated monsoon.*

Notaro *et. al.* (2011) criticise Marshall and Lynch (2008) for having *"applied a coarse global climate model coupled to a crude land surface model",* From their modelling Notaro *et. al.* (2011) found a significant climatic response to a 20% reduction in vegetation in the pre-Monsoon season, with decreases in precipitation, higher surface and ground temperatures, and enhanced atmospheric stability, leading them to conclude:

> *We find that a decrease in vegetation cover can delay the Australian monsoon and reduce early monsoon rainfall, and in this respect, our findings lend some support to the claim that Aboriginal vegetation burning practices over late Quaternary time scales impacted the northern Australian summer monsoon regime [Johnson et al. , 1999]. However, our results clearly demonstrate that the effect on the peak monsoon was limited [Pitman and Hesse, 2007; Marshall and Lynch, 2008]. But we have equally demonstrated that biophysical feedbacks associated with reduced vegetation cover can have a clear impact on the early/pre-monsoon season, leading to a significant reduction in precipitation and essentially extending the dry season.*

Wyrwoll *et. al.* (2013) reviewed previous studies and modelled the climatic impacts of reducing the total vegetation cover over northern Australia by 20% to simulate the effects of burning, concluding:

> *The results of this study indicated a significant climate response to reduced vegetation cover during the pre-monsoon period of November and December (Fig. 1a). Noteworthy is the delayed onset of the monsoon. Other prominent changes were decreases in total rainfall of more than 30 mm, higher surface and ground temperatures and enhanced atmospheric stability. ... no significant response is observed in monsoon precipitation following vegetation change, but feedbacks are evident in the pre-monsoon period.*
>
> *... we can conclude that through burning practices resulting in biome changes in northern Australia, indigenous people altered not only the ecology but also the climate of the region, effectively extending the dry season and delaying the onset of the "full" monsoon.*

For the East Asian monsoon, Fu (2003) assessed the effect of changes resulting from clearing of the potential natural landscape wrought by humans over the millennia. The impact from agrarian societies in that region have been far greater than Australia's 'firestick' hunter gatherers, with more than 80% of the region affected by conversion of various categories of natural vegetation into farmland, grassland into semi-desert and widespread land degradation. Though his study provides further evidence of the significant effect that vegetation changes can have on monsoons. Fu (2003) concluded:

> *... by altering the complex exchanges of water and energy from surface to atmosphere, the changes in land cover have brought about significant changes to the East Asian monsoon. These include weakening of the summer monsoon and enhancement of winter monsoon over the region and a commensurate increase in anomalous northerly flow. These changes result in the reduction of all components of surface water balance such as precipitation, runoff, and soil water content. The consequent diminution of northward and inland moisture transfer may be a significant factor in explaining the decreasing of atmospheric and soil humidity and thus the trend in aridification observed in many parts of the region, particularly over Northern China during last 3000 years*

In their study of East Asia's monsoon Lee *et. al.* (2011) similarly found that the "*monsoon can be weakened as potential (natural) vegetation is converted to bare ground or irrigated cropland*".

2.2. Changes since European Settlement

There have been major changes to Australia's vegetation since European settlement. Over the past 200 years some 15% of native vegetation had been cleared, and a significant proportion of the remaining vegetation has been degraded by grazing (McKeon *et. al.* 2004) and logging. Land clearing focussed on southeast Australia from 1800 to the mid-1900s, southwest Western Australia from the 1920s until the 1980s, and more recently inland Queensland. Rainfall has been declining in cleared areas, with abrupt reductions in the 1970s in south-western Australia and 1990s in south-eastern Australia. Climate change is now compounding the impacts of deforestation.

Clearing has focussed on forests and woodlands, with an estimated 20% of forests and 24% of woodlands cleared. As noted by Deo (2011) "*Within the intensive land-use zones of southeast and southwest Western Australia, approximately 50% of native forest and 65% of native woodland has been cleared or severely modified*".

Vegetation Type	***Pre-European (km2)***	***Current (km2)***	***Difference (km2)***	***Percentage lost (%)***
Forest	1,391,409	1,118,107	273,302	19.6
Woodland	2,710,459	2,066,153	644,306	23.8
Shrubland	1,470,614	1,411,539	59,075	4.0
Heath and Grassland	1,996,688	1,958,671	38,017	1.9
Total Native Vegetation	7,578,427	6,562,541	1,015,886	13.4

Aggregated changes in Australian vegetation cover, from The Native Vegetation Inventory Assessment (NVIS) of native vegetation by type prior to European settlement and as at 2001–2004 (Beeton *et al.,* 2006).

According to ABARE (2006) around 15% of the Australian continent has been cleared; 1,000,000 km^2 has been cleared for agriculture, 26,000 km^2 has been cleared for urban and residential, 1,700km^2 cleared for mining and waste, and 125,618 km^2 comprises natural and artificial water storages. Around 48% of the Australian continent comprises native vegetation used for grazing and logging; 3,600,000 km^2 of natural vegetation was used for grazing and 24,000 km^2 for logging. The remaining 37% is either protected in some form or has minimal use.

Bradshaw (2012) summarises:

> *Overall, Australia has lost nearly 40% of its forests, but much of the remaining native vegetation is highly fragmented. As European colonists expanded in the late 18th and the early 19th centuries, deforestation occurred mainly on the most fertile soils nearest to the coast. In the 1950s, south-western Western Australia was largely cleared for wheat production, ... Since the 1970s, the greatest rates of forest clearance have been in south-eastern Queensland and northern New South Wales, although Victoria is the most cleared state. Today, degradation is occurring in the largely forested tropical north due to rapidly expanding invasive weed species and altered fire regimes.*

Annual rates of clearing peaked during the 1970s when extensive areas were cleared in southwest Western Australia and Queensland for grain production and grazing pasture improvement, respectively (Deo 2011). Between 2000 and 2004 the rate of native vegetation clearance in Queensland was over 500,000 ha yr^{-1} primarily for grazing, ranking the region fifth worldwide on deforestation rate (McAlpine *et. al.* 2009). Clearing of native vegetation, particularly for cattle grazing, is still underway.

NSW has recently changed its laws to facilitate widespread clearing of native vegetation. In recent decades dryland and irrigated agriculture that was traditionally concentrated in the intensive land use zone, has expanded into marginal semiarid regions of eastern Australia, increasing land clearance and demand on scarce water resources. Ongoing clearing has been offset to some extent by an increase in woody shrubs in grazing lands over recent decades.

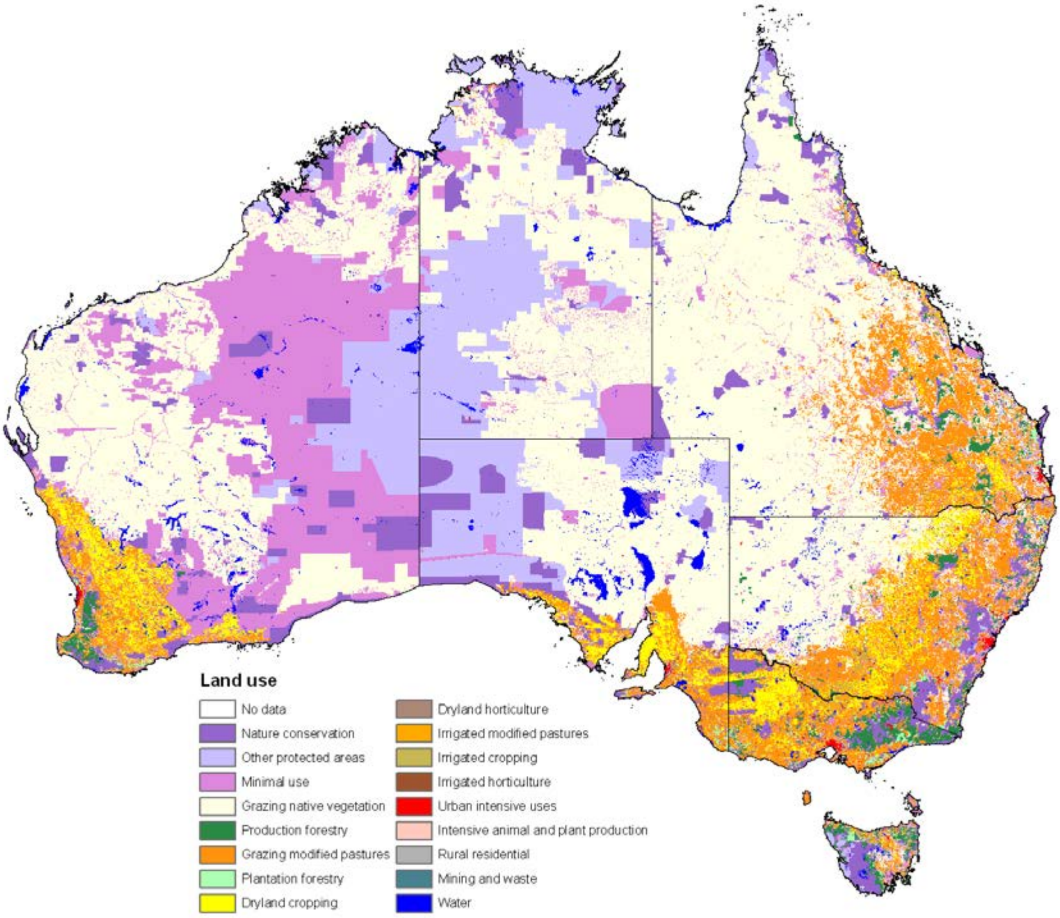


Figure 2. Land Use of Australia 2005-06, Version 4 (ABARE–BRS 2010)

Land use	Area(sq.km)	Percent (%)
Nature conservation	569,240	7.41%
Other protected areas including Indigenous uses	1,015,359	13.21%
Minimal use	1,242,715	16.17%
Grazing natural vegetation	3,558,785	46.30%
Production forestry	114,314	1.49%
Plantation forestry	23,929	0.31%
Grazing modified pastures	720,182	9.37%
Dryland cropping	255,524	3.32%
Dryland horticulture	1,092	0.01%
Irrigated pastures	10,011	0.13%
Irrigated cropping	12,863	0.17%
Irrigated horticulture	3,954	0.05%
Intensive animal and plant production	3,329	0.04%
Intensive uses (mainly urban)	16,822	0.22%
Rural residential	9,491	0.12%
Waste and mining	1,676	0.02%
Water	125,618	1.63%
No data	2,243	0.03%
Total	**7,687,147**	**100.00%**

Source: ABARE (2006).

Climate change is compounding the impacts of deforestation. Temperatures are rising. and over south-east and south-west Australia rainfall is declining, accordingly droughts in south-east Australia are intensifying with higher temperatures and prolonged heat waves.

There has been a decreasing trend in rainfall over much of southern and eastern Australia during the past 50 years, with strong seasonality and regional differentiations (Cai and Cowan 2008b, Speer *et. al.* 2011, Cai *et. al.* 2014). Speer *et. al.* (2011) identify that eastern Australia "*has experienced a decline in rainfall over the latter half of the twentieth century at a rate of between 30 and 50 mm per decade and 40–50 mm per decade since 1970*".

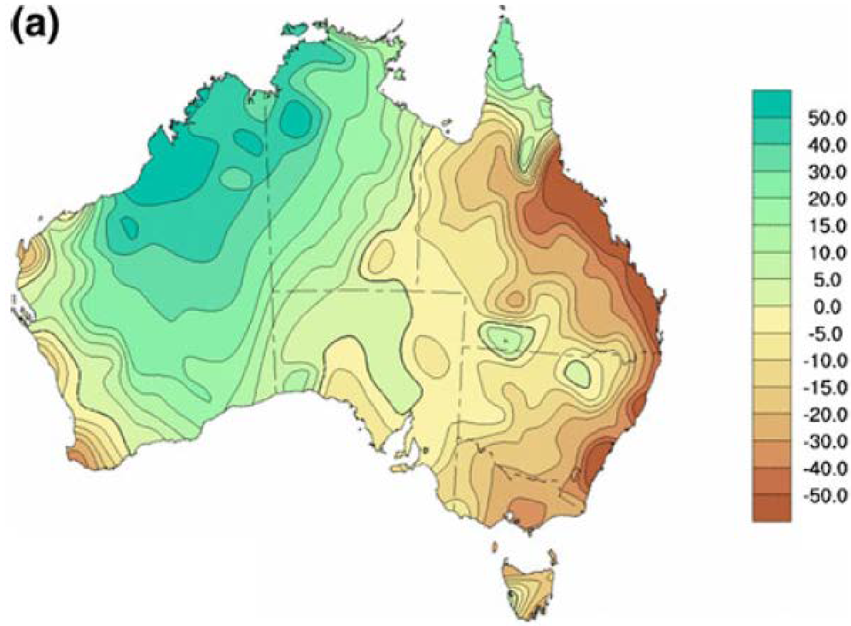


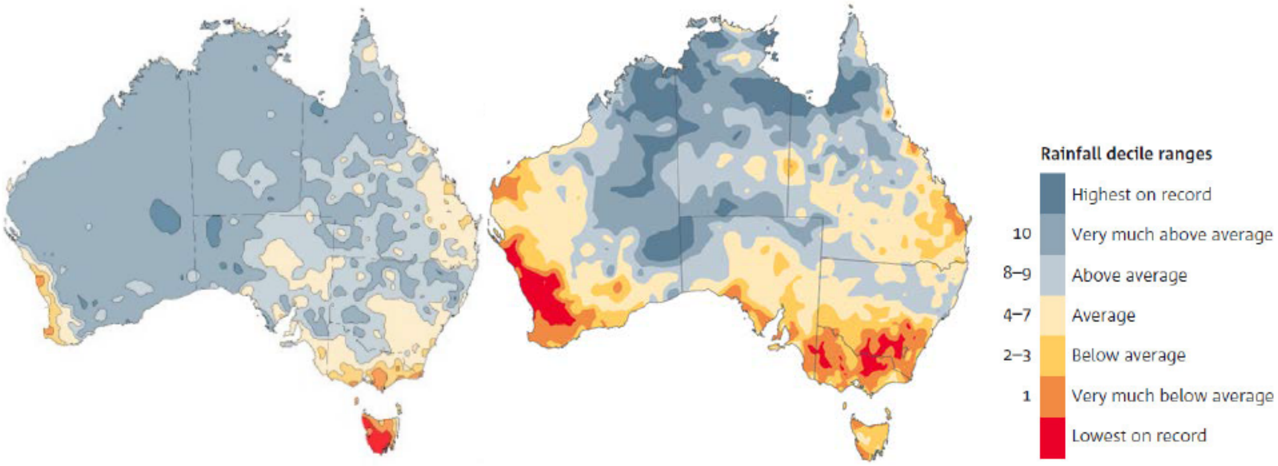
Fig. 1 from Speer *et. al.* (2011): Map of Australia highlighting the decline in annual rainfall (mm/10 years) around Australia from, 1950–2007.

Since the mid-to-late twentieth century there has been a prominent reduction in mid-to-late autumn rainfall over southeast Australia (Cai *et. al.* 2014). During 1950–2006, autumn rainfall over Victoria decreased by about 40% from its long-term seasonal average (Cai and Cowan 2008b). There has been a summer-autumn decline in rainfall over eastern Queensland of 20-30% (40–50% in coastal regions between Mackay and Townsville) since the 1950s (Cottrill 2009, Cai *et. al.* 2014). These rainfall declines have been characterised by step-wise seasonal reductions. The southern drying trends are characterised by a 10-20 percent reduction (expressed as a step change or series of step-changes) in cool season (April –September) rainfall across the south of the continent (Braganza *et al.* 2011). Significant rainfall declines have persisted since around 1970 in the south-west and since the mid-1990s in the south-east (Braganza *et al.* 2011). In south-west Australia there was an abrupt decline of around 14% in the mid 1970s (Bates *et. al.* 2008), since 1996 this decline from the long-term average has increased to around 25% (BoM 2016).

During the period between the mid-1990s and late 2000s, many Australian regions were plagued by concurrent severe droughts, which later became known as the Millennium Drought. This was the most severe drought experienced by southern Australia since instrumental record began in the 1900s (Cai *et. al.* 2014). Streamflows declined in a greater proportion than rainfall, as identified by CSIRO (2010) "*the 15 per cent reduction in rainfall during 1936-1945 led to a 23 per cent reduction in modelled annual streamflow in the southern Murray-Darling Basin ..., while the 13 per cent reduction in rainfall during 1997-2006 led to a streamflow decrease of 44 per cent*". From the late

1990's to 2001 there has been a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012), causing the proportion of rainfall that became runoff to drop by an average 50%. In Western Australia this decline appears to be linked to the conversion of native forests to regrowth with higher evapotranspiration.

It appears that global warming was a contributing factor to the Millennium Drought but could not account fully for the severity of the drought (CSIRO 2010, Cai *et. al.* 2014). Cai *et. al.* (2014) compared the outcomes from the Millennium Drought with climate change models, concluding "*model results confirm that the drought over southern Australia is at least in part attributable to a recent anthropogenic-induced change in the climate ... despite models severely underestimating the magnitude of this shift. The changes in these climate indices are partially attributable to greenhouse warming ...*".



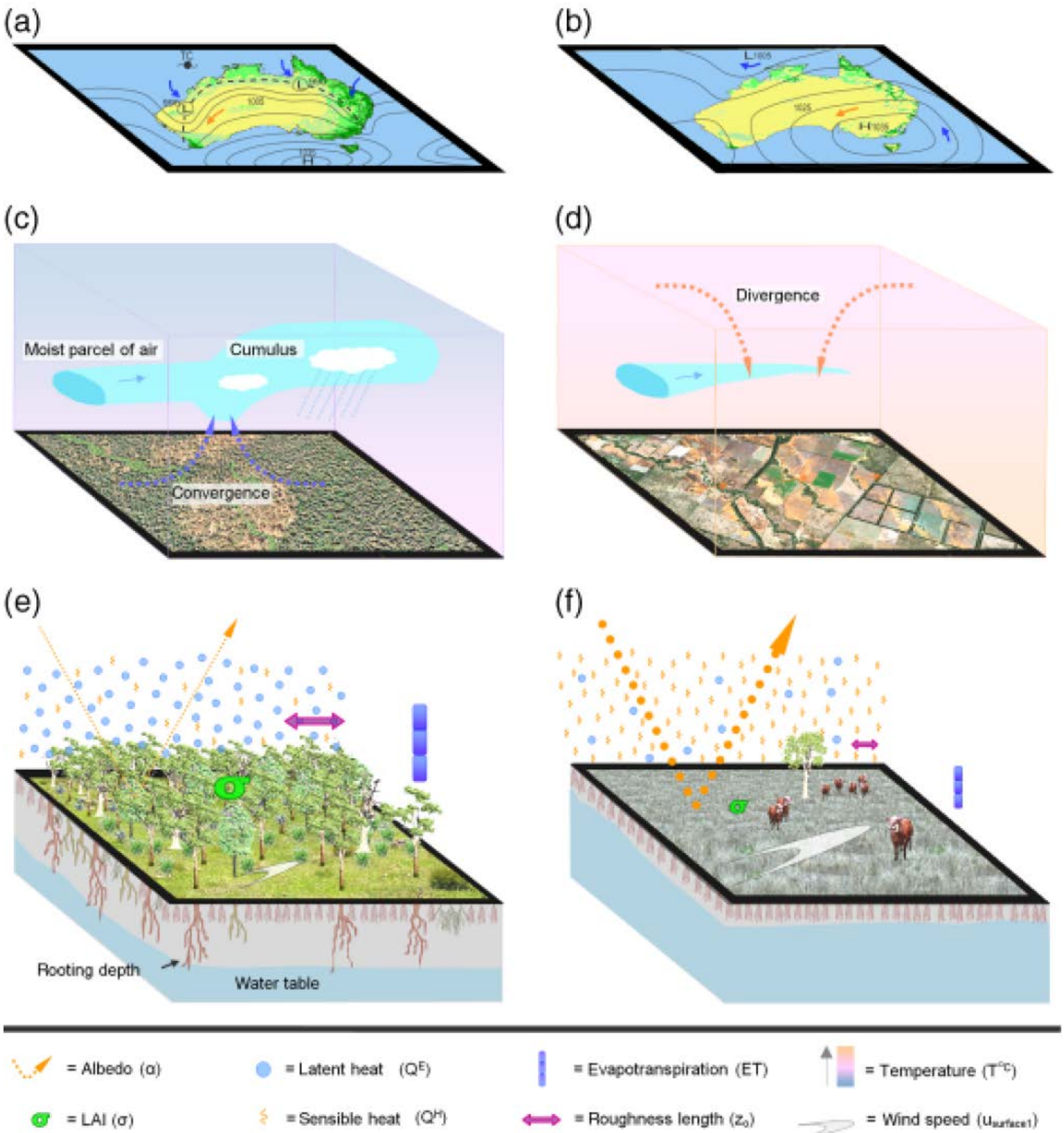
LEFT: Rainfall deciles for October-April 1997-2013 relative to 1900-2013. RIGHT: Rainfall deciles for April-September1997-2013 relative to 1900-2013 SOURCE: Braganza et. al. (2015). Note the striking correlations with the previous map of land uses, reflecting Land Cover Change.

Braganza *et. al.* (2015) consider that it has now been reasonably established that the decline in rainfall has been associated with both fewer rain-bearing systems, and less rainfall from those systems that do cross the region. Though the dynamics of this decline are poorly understood (Cai and Cowan 2008b). Speer et. al. (2011) consider the variability is partially related to long term climatic patterns: El Niño-Southern Oscillation (ENSO), the inter-decadal Pacific oscillation (IPO) and the southern annular mode (SAM). Cottrill (2009) linked rainfall declines in Queensland to mean sea level pressure, and changes in the 'subtropical ridge' and SAM, though recognised that deforestation played a part.

All the indications are that because of climate change, in southern and eastern Australia these trends of declining rainfall will continue (Bates *et. al.* 2008, Cai and Cowan 2008a, Mpelasoka *et.al.* 2007, CSIRO and Bureau of Meteorology 2015). Mpelasoka *et.al.* (2007) projected that "*by 2030, soil-moisture-based drought frequency increases 20–40% over most of Australia with respect to 1975–2004 and up to 80% over the Indian Ocean and southeast coast catchments by 2070*". Based on CSIRO and Bureau of Meteorology (2015) climate change projections:

- in southern mainland Australia, winter and spring rainfall is highly likely to decrease, possibly by as much as 50% in south-west Western Australia by 2090
- it is likely that rainfall will decrease in south-western Victoria in autumn and in western Tasmania in summer
- for eastern Australia it is likely that winter rainfall will decrease by 2090

- it is highly likely that extreme rainfall events will increase in intensity, except possibly in south-west Australia
- the frequency and intensity of droughts are likely to increase, particularly in southern Australia.



A schematic model from McAlpine *et. al.* (2009) showing the effect of land cover change on the boundary layer properties at the continental scale (a, b), regional scale (c, d) and landscape scale (e, f). The models on left show intact Australian native woodlands, models on the right show feedbacks following clearing. At landscape scale, the major transformations (e > f) include increased sensible heat flux, albedo, and wind speeds. The leaf area index (LAI), vegetation fraction, evapotranspiration, latent heat flux, surface roughness and soil moisture have decreased. At the regional scale, these changes in fluxes alter the feedbacks to broader exchange of moisture between the land surface and the boundary layer, and regions of forced convection and advection (c > d), which in many cases have contributed to decreases in cumulus cloud formation. The potential for cumulative effects of regional changes in land cover on pressure systems are shown schematically as D isobars (a > b). Artwork by Justin Ryan.

While climate change due to increasing atmospheric CO^2 appears to have been a significant factor in rainfall declines, there is growing evidence that land use change has played a major role. The co-incidence of rainfall decline with land clearing is unlikely to be due to chance.

Gordon *et. al.* (2003) estimate that shift in Australia land use from 1780 to 1980 resulted in the conversion of around $80x10^6$ ha of woody vegetation (wet dense forest, open forest, woodland) to grassland/croplands, causing in the order of a 10% decrease in water vapour (evapotranspiration) flows, which corresponds to an annual freshwater flow of almost 340 km^3, or "*more than 15 times the volume of run-off freshwater that is diverted and actively managed in the Australian society*".

Narisma and Pitman (2003) undertook modelling to identify the likely consequences of changes between natural (1788) and current (1988) vegetation cover, considering reduced evaporation was the main influence that explained the reduced rainfall, and noting:

> *Results show that the impact of land cover change on local air temperature is statistically significant at a 99% confidence level. Furthermore, there are indications that the observed increase in local maximum air temperatures in certain regions of Australia can be partially attributed to land cover change. The results are evidence of statistically significant changes in rainfall, and the sign of these changes over Western Australia in July, and the lack of any simulated changes in January, agree with observations. These results provide further evidence of large-scale reductions in rainfall following land cover change. Changes in wind speed are also simulated and are consistent with those expected following land cover change. The results indicate that attempts to identify greenhouse-related warming in Australian air temperature records should account for the effects of both land cover change and increasing CO^2 concentrations since both types of anthropogenic forcing exist in long-term observational records.*

Syktus *et.al.* (2007) undertook a comparison of pre-European and modern day land surface parameters, identifying that due to land cover change average rainfall decreased by 2.5% in Queensland, 5.2% in eastern New South Wales/Victoria and 0.9% in south-western Australia, summarising their findings:

> *... an increase in albedo for all regions were land cover change had occurred. ... increased strength of surface winds by reducing aerodynamic drag ... modified surface evaporation, latent and sensible heat fluxes and planetary boundary layer properties ...The increase in near surface wind amplified the shift from moist northeast tropical air to cooler and drier southeast flow from the Tasman Sea, resulting in the decreased rainfall. Results showed that the regional perturbation of vegetation can possibly magnify the impact of natural mode of individual El Niños, which together with rainfall deficiency, could have a strong impact on climate conditions (e.g. droughts) in eastern Australia. Hence, the replacement of native vegetation with seasonal cropping and improved pastures is likely to be contributing to more severe droughts and increased demand for water.*

McAlpine *et. al.* (2007) undertook modelling to compare the effects on Australian climate based on differences between pre-European and 1990 vegetation cover, finding:

> *Consistent with actual climate trends since the 1950s, simulated annual and seasonal surface temperatures showed statistically significant warming for eastern Australia (0.4-2℃) and southwest Western Australia (0.4-0.8℃), being most pronounced in summer. Mean summer rainfall showed a decrease of 4-12% in eastern Australia and 4-8% in southwest Western Australia which coincided with regions where the most extensive land clearing has occurred.*

> *Further, the study found an increase in temperatures on average by 2°C, especially in southern Queensland and New South Wales, for the recent 2002/2003 drought.*
>
> *The findings suggest that the large scale clearance of native vegetation is amplifying the adverse impacts associated with El Niño drought periods, which together with rainfall deficiency, is having a strong impact on Australia's already stressed natural resources and agriculture.*

Based on McAlpine *et. al.* (2007) and Syktus *et.al.* (2007), McAlpine *et. al.* (2009) derived regionally averaged values of mapped surface parameters for pre-European and modern-day land cover characteristics and the corresponding changes in regional climate over eastern New South Wales in summer, identifying:

> *During the summer season in eastern New South Wales, the area-averaged changes in surface characteristics (Fig. 5a) showed large decreases in vegetation fraction (19%) and LAI [leaf area index] (23%), and a resulting 7% increase in albedo. A corresponding reduction in surface roughness (46%) coincided with a 9% increase in wind speed, while summer surface temperatures exhibited an average warming of* [approx.] *0.6°C. This warming was related to an increase in surface absorption of incoming short-wave radiation by 5.2%. The area-averaged rainfall decreased by 5.2%. The area-averaged energy fluxes showed a reduction in latent heat flux (7.3%) and an increase in sensible heat flux (1.3%).*

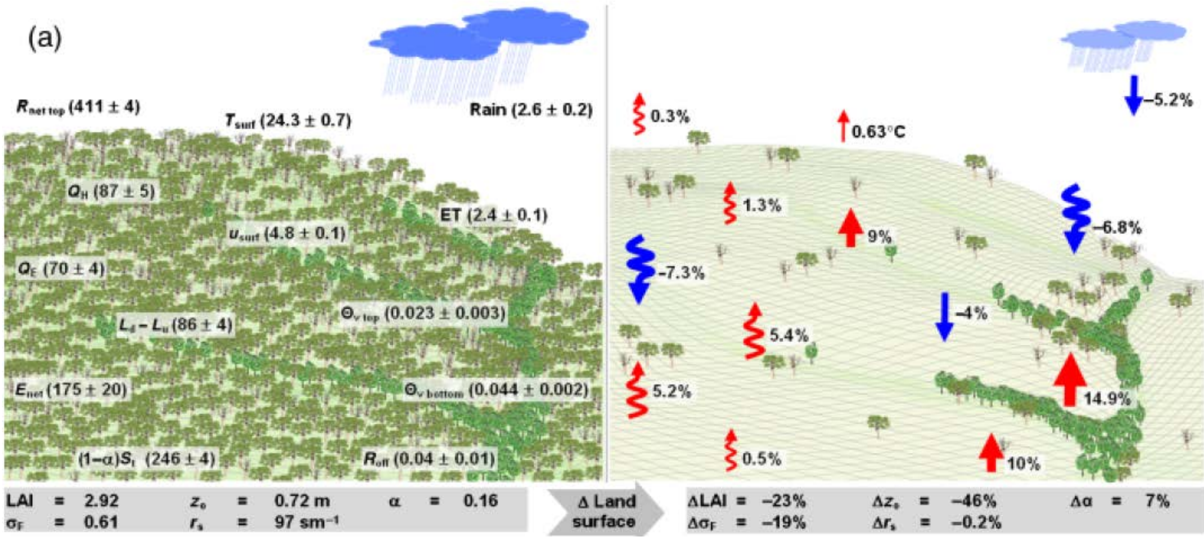


Fig. 5 from McAlpine *et..al.* (2009) showing a hypothetical ecosystem in the Australian summer for eastern New South Wales, both pre-European and today. LEFT: a pre-clearing (natural) ecosystem with the initial land surface properties/fluxes with natural vegetation (bottom box) and corresponding climate responses (labels on landscape model); RIGHT: changes in land surface properties/fluxes due to clearing (bottom box) and corresponding climate responses (labels on landscape model) in a present-day-modified landscape. Note: blue arrows (decreases), red arrows (increases), arrow width relative to magnitudes of change. a, surface albedo; LAI, leaf area index; sF, vegetation fraction; z0, surface roughness; rs, stomatal resistance; Tsurf, surface temperature; Rain, rainfall; QH, sensible heat flux; QE, latent heat flux; Ld_Lu, net surface long-wave radiation; (1_a)St, net surface short-wave radiation; Enet, net surface energy; Rnet top, net radiation at top of atmosphere; usurf, surface windspeed; (yv top , Yv bottom), top and bottom layer soil moisture and ET, evapotranspiration rates. Artwork by Justin Ryan.

McAlpine *et..al.* (2009) summarise:

> *The historical clearing of approximately 15% of the continent for agriculture is likely to have contributed to a hotter and drier climate and exacerbated the effect of the El Niño by increasing the severity of droughts, especially in south-east Australia. This problem is being compounded by the interaction of contemporary land use pressures and an emerging trend towards a hotter and more-drought-prone climate driven by increased anthropogenic greenhouse gases.*

Deo *et.al.* (2009) modelled the consequences of land cover change (LCC) for the period 1951–2003 to quantify the impact of LCC on selected daily indices of climate extremes, finding:

> *The results showed: an increase in the number of dry and hot days, a decrease in daily rainfall intensity and wet day rainfall, and an increase in the decile-based drought duration index for modified land cover conditions. These changes were statistically significant for all years, and especially pronounced during strong El Niño events. Therefore it appears that LCC has exacerbated climate extremes in eastern Australia, thus resulting in longer-lasting and more severe droughts.*

As noted by Deo (2011)

> *Clearly, these studies have demonstrated that LCC has exacerbated the mean climate anomaly and climate extremes in southwest and eastern Australia, thus resulting in longer-lasting and more severe droughts.*

In relation to 'land use/land cover change' (LUCC) McAlpine *et. al.* (2009) warn:

> *The consequences of ignoring the effect of LUCC on current and future droughts in Australia could have catastrophic consequences for the nation's environment, economy and communities. We highlight the need for more integrated, long-term and adaptive policies and regional natural resource management strategies that restore the beneficial feedbacks between native vegetation cover and local-regional climate, to help ameliorate the impact of global warming.*

McAlpine *et. al.* (2009) emphasise:

> *Reducing greenhouse gas emissions is essential but not sufficient as a climate change mitigation strategy. Anticipatory policies need to be explored and tested aiming at reduction in land use pressures and restoration of native vegetation cover in order to try to avoid likelihood of irreversible climate change. Potential mitigation and adaptation options include: (1) tighter legislative controls on the clearing of native vegetation, including regrowth native vegetation in previously cleared subtropical landscapes; (2) expanded investment in ecological restoration based on the strategic integration of native vegetation with production systems in the highly modified agricultural landscapes; (3) an evaluation of the long-term viability of marginal cropping and grazing lands and their vulnerability to soil and vegetation degradation; and (4) adaptive management of stocking rates according to climate conditions.*

2.3. Groundwater-Associated Salinity

Over many thousands of years, salt has been accumulating in Australian soils delivered by wind and rain from the sea, or left-over from ancient inland seas. The minimal runoff has allowed the salts introduced through rainfall or rock weathering to build up in the soil below the depth of plant roots. Williams *et. al*. (2002) consider:

> *It is well documented that healthy native ecosystems within catchments are in hydraulic and salt balance ... The input of salt to the catchment is balanced by the salt discharged from the*

> *catchment. Once clearing occurs and a agriculture is introduced, the salt discharged from the catchment begins to greatly exceed the salt entering the catchment.*

Rengasamy (2006) observes:

> *Under native vegetation, leaching of salts from the permeable soil due to natural processes led to salt storage in deep regolith or the accumulation of salts in the shallow groundwater. ... As long as the water table was 4 m below the surface, saline groundwater did not affect native vegetation while some species could cope with shallower water tables.*

One of the principal impacts of deforestation is the raising of groundwater levels. Rising groundwaters can be problematic where aquifers have been disconnected from throughflows and have thus accumulated salts. The total salinity and the composition of many saline groundwater samples in Australia are similar to seawater. Salinisation of land is not a new problem, in southern Mesopotamia and in several parts of the Tigris–Euphrates valley it destroyed the ancient societies that had successfully thrived for several centuries (Rengasamy 2006). Salinisation was recognised as a potential problem as early as 1864 in Western Australia and the hydrological factors responsible were identified in 1897. The major attention for salinity in Australia is on irrigation-induced salinity in the Murray-Darling basin and dry-land salinity associated with shallow groundwater, particularly in Western Australia (Rengasamy 2006).

Groundwater-associated salinity is a form dry-land salinity resulting in the visual scalding of soil surfaces, usually at the foot of slopes and in valley floors, associated with a rising saline water table. The clearing of woody vegetation reduces the rooting depth of vegetation and evapotranspiration, the reduced transpiration of deeper soil moisture can allow water-tables to rise, in places allowing saline watertables to rise to the surface and enter streams (Allison *et. al.* 1990, Ruprecht and Schofield 1991a, NLRWA 2001, Williams *et. al*. 2002, Gordon *et. al.* 2003, Silberstein *et. al.* 2003, Bari and Ruprecht 2003, Hatton *et. al.* 2003, Rengasamy 2006).

Salinisation is generally a problem of lower rainfall areas, as noted by Bari and Ruprecht (2003):

> *The permanent groundwater system in the high rainfall areas (annual rainfall above 1100 mm) usually discharges to streams and keeps these areas leached of salt. As such, the high rainfall areas are generally of low salinity hazard. In the low rainfall areas, the deep groundwater tables are far below the stream bed and do not contribute to streamflow. As a consequence, salt has accumulated in the unsaturated zone and these areas pose a high potential salinity hazard. ...*

Silberstein *et. al.* (2003) describe the process of dryland salinity:

> *However, clearing of the native vegetation since European settlement has tipped over this delicate balance and caused increased recharge, which led to rapid rise in groundwater tables and increased groundwater discharge to streams.*
>
> *...*
>
> *When the watertable rises the salt is dissolved. This groundwater flow carries huge quantities of salt to the surface, discharging to streams and concentrated by evaporation, causes large scale land and stream degradation.*
>
> *...*
>
> *As a result of the shallower saline watertables, evaporation at the soil surface brings salt to the surface through capillary rise, and accumulates in large white crusted salt scalds. When rain falls the surface accumulations of salt wash off and are rapidly transported to the*

stream. Additionally, the shallow watertable means that the infiltration capacity of catchments is reduced and the runoff/rainfall ratio increased.

Hatton *et. al.* (2003) summarise the experience in south-western Australian:

> *The hydrological and hydrogeochemical changes induced by widespread clearing of this vegetation for dryland agriculture are profound and enduring. Run-off onto and through the valley floors has increased by a factor of five; combined with local rainfall on these valley floors, the resulting increase in groundwater recharge is filling the deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on the slopes and ridges, with saline watertables rising in these lateritic formations as well, providing additional hydraulic heads forcing groundwater towards the valleys.*

Ruprecht and Schofield (1991a, b) partially deforested (western 53% of the catchment) a small (344ha) experimental catchment in southwest Western Australia in 1976 to study the effects of agricultural development on water quantity and quality, finding:

> *However, since 1987, stream salinity increased dramatically as the ground water approached the ground surface, and by 1989 reached an annual average of 290 $mgl^{-1}Cl^{-}$. The daily maximum in 1989 was 2200 $mgl^{-1}Cl^{-}$ compared with 92 $mgl^{-1}Cl^{-}$ from 1976 to 1986. The catchment changed from net salt accumulation pre-clearing to net salt export after 1987. Thirteen years after clearing, the groundwater level, stream yield, stream salt load and stream salinity had not reached equilibrium but were all still increasing*

Bari and Ruprecht (2003) further document the salinity problem:

> *Salt storage in the soil profile at the Wights and Lemon catchments is 0.4 kg/m^2 and 2.3 kg/m^2 respectively (Johnston 1987; Bari et al. 2003). The annual stream salinity at the Wights catchment increased immediately after clearing from an average of 360 to 515 mg/L TDS (Fig. 9). The average annual salt load increase at the Wights catchment was 14-fold (compared with the control catchment). At the Lemon catchment, from 1977–87 (before the groundwater system was connected to the streambed), the average annual stream salinity rose from 80 to 127 mg/L TDS. After 1987 when the groundwater system reached the streambed, the stream salinity generation process changed significantly and annual average salinity increased systematically to 1700 mg/L TDS. The annual stream salt load increased 180-fold compared with the control catchment.*

To date, salinisation in southern Australia has generally been limited to areas where ground water was originally relatively near the land surface, though in areas with low rainfall and deep groundwaters it can take tens or hundreds of years for saline groundwater to rise to the surface, so there are many areas where the impacts of clearing undertaken decades ago are yet to materialise. From their study of land clearance and river salinisation in the western Murray basin, Allison *et. al.* (1990) concluded:

> *Rates of groundwater recharge under native mallee vegetation in the western Murray Basin are less than 0.1 mm $year^{-1}$. After clearing, the mean recharge rates increase by approximately two orders of magnitude to between 5 and 30 mm $year^{-1}$. The water table over much of the western Murray Basin occurs more than 30 m below the land surface, and this, coupled with the low rates of recharge, results in a considerable delay in the response of the aquifer to the increased recharge. ... The development of land salinisation has thus been slow, and restricted to areas where the water table was initially within only a few metres of the ground surface.*

> *... The increased inflow of saline water to the River Murray will cause its salinity to steadily increase over at least the next 200 years unless a combination of land management and engineering strategies is adopted.*

The National Land and Water Resources Audit (NLRWA 2001) identifies that recent estimates indicate that *ca*. 5.7 million hectares of Australia are currently at risk of dryland salinity, which could rise to over 17 million hectares by 2050. Western Australia is the worst off with 33% of the land area at risk of salinisation, followed by Victoria.

Williams *et. al*. (2002) consider that "*Dryland salinity is undoubtedly the greatest and most intractable threat to the health and utility of Australia's rivers, soil and vegetation ... if we do not find and implement effective solutions, the area of land affected by dryland salinity is likely to rise to between 10 and 12 million ha over the next fifty years*", noting:

> *Western Australia has the greatest area of dryland salinity at present (1.8 million ha) with the potential to rise to 6.1 million ha; all the rivers of south-western Western Australia are salinised or salinising. A similar picture is emerging for South Australia, where Jolly et al. (2000a) showed that all surface waters are either salinised or at risk of serious salinisation. New South Wales is of critical concern, with 7.5 million ha potentially at risk*

Gordon *et. al.* (2003) identify that "*production loss due to saline river water, health hazards, deterioration of agricultural lands, destruction of infrastructure in rural and urban areas, and loss of biodiversity and ecosystem services in both terrestrial and aquatic environments are among the social costs*" of dryland salinisation.

As salinisation develops it kills the affected vegetation, creating a positive feedback that helps perpetuate the problem.

The salinisation of the landscape resulting from deforestation provides a clear and urgent reason to stop land clearing in any landscapes where there is a risk of this occurring. While considerable effort has gone into identifying such areas, they do not appear to be off-limits for further deforestation.

2.4. The Western Australia Experience

The effects of deforestation in south-west Western Australia (SWWA) on streamflows have been extensively studied because the vegetation has been finely balanced with rainfall, using most of the available rainfall and leaving little excess for stream flow. The region is used in this review as a case study of the problems being experienced across southern and eastern Australia as a result of deforestation and land degradation.

SWWA can be defined as a 25,000 km^2 coastal plain (the coastal strip) stretching 500 km from north to south and 30-100 km wide. Flanked to the east by 300-500 m high hills (the Darling scarp) with a large flat plain 300 m above sea level that covers 171,000 km^2 to the northeast (the wheatbelt). This is separated from land that is too dry for agriculture (the goldfields) to the east by the rabbit fence. In SWWA almost all of the rain consistently arrives during the months of April to October brought on by cold fronts moving west from the Indian Ocean over the coast. (Andrich and Imberger 2013)

Deep groundwater supplies have been crucial in maintaining tree transpiration during the severe dry periods that are often experienced. Silberstein *et. al.* (2003) identify that "*prior to clearing for agriculture the deep rooted perennial native vegetation used virtually all the available rainfall, and maintained a very deep or non-existent watertable. What little groundwater flow there was, was very slow due to the low gradients and low transmissivities*". Silberstein *et. al.* (2001) observe "*the jarrah (Eucalyptus marginata) forest in southwest Western Australia is capable of maintaining vigorous growth through severe dry summers, during which there may be little or no rain for close on 6 months. in part because they can access the deep soil water to maintain high evaporation rates in the summer months and avoid significant water stress*".

Hatton *et. al.* (2003) summarise the south-western Australian experience with widespread clearing:

> *The accumulation and distribution of salt, the rudimentary aquifers with deep watertables, the intermittent flooding and subsequent transpiration of water from the valley sediments, and the low yields of water reaching the ocean were a product of the underlying physical environment and vegetation types capable of using deeply infiltrated water through the dry season. The hydrological and hydrogeochemical changes induced by widespread clearing of this vegetation for dryland agriculture are profound and enduring. Run-off onto and through the valley floors has increased by a factor of five; combined with local rainfall on these valley floors, the resulting increase in groundwater recharge is filling the deep sedimentary materials and bringing highly saline water to the surface. Diffuse recharge has also increased on the slopes and ridges, with saline watertables rising in these lateritic formations as well, providing additional hydraulic heads forcing groundwater towards the valleys.*

In the mid-1970s Southwest Western Australia (SWWA) experienced a step-wise change in climate manifesting itself as a rapid 15–20% decrease in rainfall and an associated >50% decrease in runoff into Perth's drinking water catchments (Bates *et. al.* 2008, Petrone *et. al.* 2010). Since 1996 this decline in rainfall from the long-term average has increased to around 25% (BoM 2016). From the late 1990's to 2001 there was a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012), causing the proportion of rainfall that became runoff to drop by an average 50%.

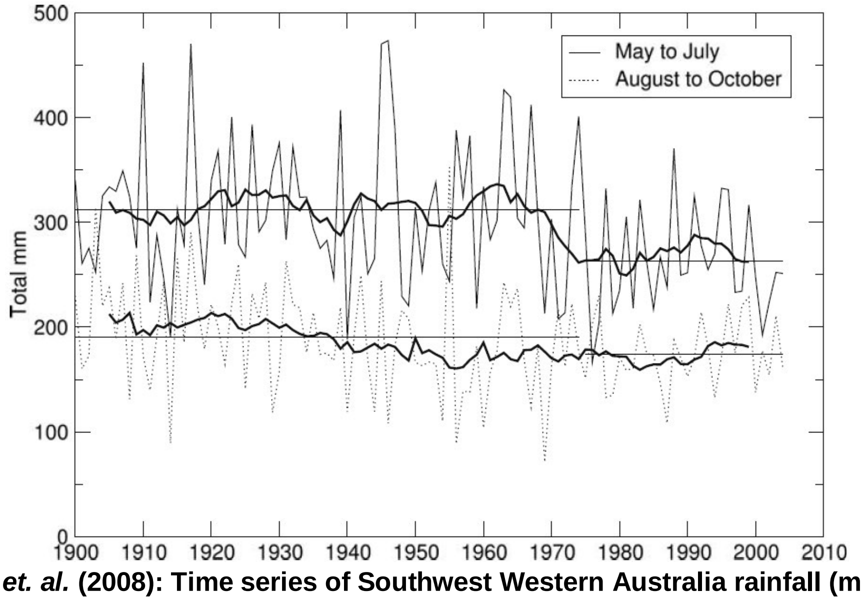


Fig. 4 from Bates *et. al.* (2008): Time series of Southwest Western Australia rainfall (mm). Solid trace depicts early winter (May to July) totals and dotted trace late winter (August to October) totals. Means for the periods 1900 to 1974 and 1975 to 2004 are represented by horizontal lines

Ongoing declines in streamflows, and tree deaths due to apparent water stress in the *Eucalyptus gomphocephala* (Tuart) forest in southern SWWA and *Eucalyptus wandoo* woodland in eastern SWWA, have heightened concern that the rainfall decline is intensifying (Bates *et. al.* 2008). Climate models suggest that rainfall in the region will go on declining, and evaporation increase, as the earth warms (Bates *et. al.* 2008).

This abrupt decline in rainfall has been partially attributed to a poleward shift of the extratropical jet resulting in a decrease of westerly winds bringing less rainfall over land (i.e. Bates *et. al.* 2008), though other studies "*suggest that effects of land cover change (LCC) may also be substantial and this has been confirmed by modeling studies*" (Nair *et. al.* 2011). Andrich and Imberger (2013) compiled rainfall and clearing records for SWWA, considering that the "*data do not support the hypothesis that global warming has shifted rain bearing cold fronts southward*", and that "*natural variation and global warming may be contributing at most to a combined 12.5% decline in rainfall*".

By 1950, 30% (68,000 km^2) of the SWWA arable area had been cleared. From 1950 to 1980, 42% of SWWA land (82,000 km^2) was cleared with the introduction of new machinery and active government promotion of large-scale clearing. Between 1980 and 2000 the rate of land clearing slowed with 4% (9,000 km^2) of native vegetation cleared. By 2002 dryland salinity was recognized to affect over 5,000 km^2 of previously productive agricultural land. (Andrich and Imberger 2013).

From their comparison of land clearing and rainfall records Andrich and Imberger (2013) found that "*deforestation causing native vegetation to reduce from 60% to 30% of the coastal strip correlates with a 15.2% to 18% decline in annual winter rainfall (relative to rainfall at the coast)*", concluding *"that 50-80% of the 30% rainfall decline observed since 1970 could be attributed to land-use change".*

Pitman *et.al.* (2004) undertook modelling to assess the likely contribution of Land Cover Change (LCC) to the declining rainfall, concluding:

> *We find that land cover change explains up to 50% of the observed warming. Following land cover change, we also find, in every simulation, a reduction in rainfall over southwest Western Australia and an increase in rainfall inland that matches the observations well. We show that the reduced surface roughness following land cover change largely explains the simulated changes in rainfall by increasing moisture divergence over southwest Western Australia and increasing moisture convergence inland. Increased horizontal wind magnitudes and suppressed vertical velocities over southwest Western Australia reduce the likelihood of precipitation. Inland, moisture convergence and increased vertical velocities lead to an increase in rainfall. Our results indicate that rainfall over southwest Western Australia may be returned to the long-term average through large-scale reforestation, a policy option within the control of local government.*

Timbal and Arblaster (2006) undertook modelling that also indicated Land Cover Change is likely to be a significant contributor to the declining rainfall:

> *We found that vegetation cover affects modelled rainfall in the region and enhances the model response to anthropogenic atmospheric forcings (including greenhouse gases, ozone and sulphate aerosols), which were found in a previous study to explain part of the observed rainfall decline. ... While the rainfall response to anthropogenic forcings is driven mostly by the changes in pressure, the land cover influences directly the modelled rainfall (large-scale and total) and thus indirectly the downscaled rainfall. A plausible trigger appears to be the reduction of roughness length.*

Kala *et. al.* (2011) modelled a summer and a winter cold front in SWWA to assess the impacts of land clearing, and:

> *found that land-cover change results in a decrease in precipitation for both fronts, with a higher decrease for the summer front. The decrease in precipitation is attributed to a decrease in turbulent kinetic energy and moisture flux convergence as well as a increase in wind speed within the lower boundary layer. The suggested mechanism is that the enhanced vertical mixing under pre-European vegetation cover, with the decrease in wind speeds close to the ground, enhance microphysical processes leading to increased convective precipitation. The higher decrease in precipitation for the summer front is most likely due to enhanced convection during summer.*

Many authors have taken advantage of a 750 km rabbit-proof fence in south-western Australia that separates 13 million hectares of croplands from the remnant native vegetation to the east to assess climatic changes across the boundary. The problem is that the fence is the divide between land suitable for agriculture from land too dry for agriculture, with most vegetation to the east of the fence 0.5 m and 2.0 m high. They have all observed preferential cloud formation over native vegetation compared to the croplands (Huang *et. al.* 1995, Lyons 2002, Junkermann et.al. 2009, Nair et. al. 2011). The groundwater table in the agricultural region rose from >20m deep to around 2m within 30 years since 1950 with a concurrent increase in groundwater salinity (Junkermann et.al. 2009).

Huang *et. al.* (1995) considered "*that convective mixing over the cleared land is no longer able to reach the lifting condensation level for a significant period of the year. This implies a decrease in convective cloud formation and a reduction in the convective enhancement of rainfall*".

Lyons (2002) considered "*that the darker albedo of the native vegetation provided that local forcing to assist in convective development over the native vegetation in contrast to the lack of development over the agricultural land. Thus changes in the surface albedo through clearing for agriculture have decreased the local forcing necessary to trigger storm development*".

Junkermann *et.al.* (2009) found:

> *Besides different meteorology, we found a significant up to now overlooked source of aerosol over the agriculture area. The enhanced number of cloud condensation nuclei is coupled through the hydrological groundwater cycle with deforestation. Modification of surface properties and aerosol number concentrations are key factors for the observed reduction of precipitation.*

Nair *et. al* (2011) considered the primary cause for rainfall decrease in the area subject to Land Cover Change (LCC) is due to changes in low-level convergence, caused by alteration of both west coast trough dynamics and aerodynamic roughness, noting:

> *Observations and numerical model analysis show that the formation and development of the west coast trough (WCT), which is a synoptic-scale feature that initiates spring and summertime convection, is impacted by land cover change and that the cloud fields induced by the WCT would extend farther west in the absence of the LCC. The surface convergence patterns associated with the wintertime WCT circulation are substantially altered by LCC, due to changes in both WCT dynamics and surface aerodynamic roughness, leading to a rainfall decrease to the west of the rabbit fence.*

Studies in 27 experimental catchments in the south–west of Western Australia examined the impacts of land use practices such as clearing for agricultural development, forest harvesting and regeneration, forest thinning, bauxite mining and reforestation on water yields to streams (Bari and Ruprecht 2003). They found that clearing led to permanent increases of water yield of about 30% of annual rainfall for high rainfall (1100 mm mean annual rainfall) and 20% of annual rainfall for low rainfall areas (900 mm annual rainfall). Logging, thinning and reafforestation of mines led to initiation of regrowth with increasing evapotranspiration.

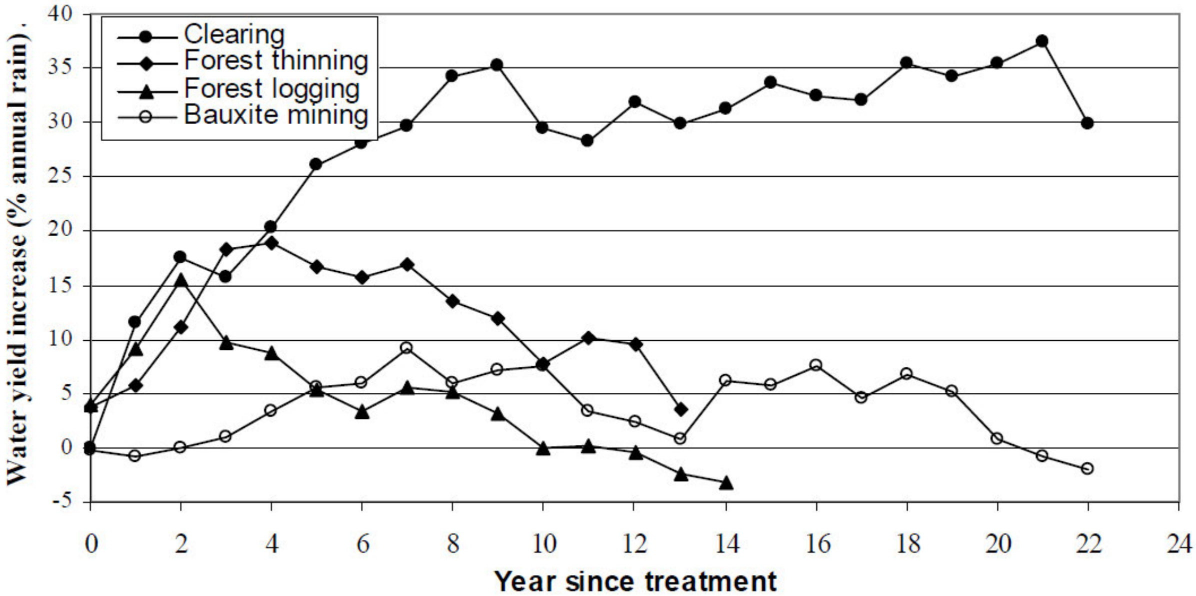


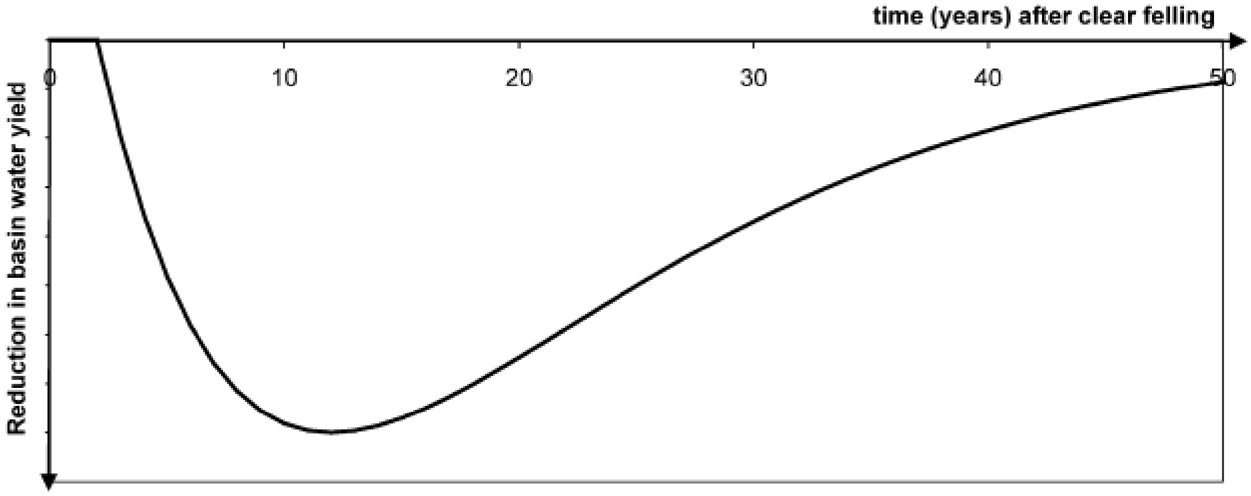
Figure 19 from Bari and Ruprecht (2003): Comparison of stream yield responses to land use practices in the south-west Australian 'High Rainfall Zone'.

From their assessment of these catchments Silberstein *et. al.* (2003) identify:

> *The proportion of rainfall that becomes stream flow (runoff coefficient) has increased as a response to clearing, and continued to increase through time in the cleared catchments ...*
>
> *For all occurrence frequencies there is more flow in the cleared catchments and much fewer days without flow than in the catchments still forested over the same time period. These trends increase in time. ...*
>
> *Following clearing, runoff coefficient has risen by a factor of 5 in the wetter catchments, about 10-20 in the intermediate catchments, and up to 100 times in the drier catchments, which have almost no runoff under natural conditions. ...*

While the evidence is that permanent clearing of native vegetation results in an increase in runoff to streams, which can largely be attributed to a reduction in evapotranspiration, it is equally clear that activities such as logging and thinning can result in reduced runoff over time. The generalised pattern following heavy and extensive logging of an oldgrowth forest is for there to be an initial increase in runoff peaking after 1 or 2 years and persisting for a few years. Water yields then begin to decline below that of the oldgrowth as the regrowth uses more water. Water yields are likely to reach a minimum after 2 or 3 decades before slowly increasing towards pre-logging levels in line with forest maturity. (Kuzcera 1987, Vertessy *et. al.* 1998, Cornish and Vertessy 2001, Bari and Ruprecht 2003, Brown *et. al.* 2005, Burrows *et. al.* 2011).

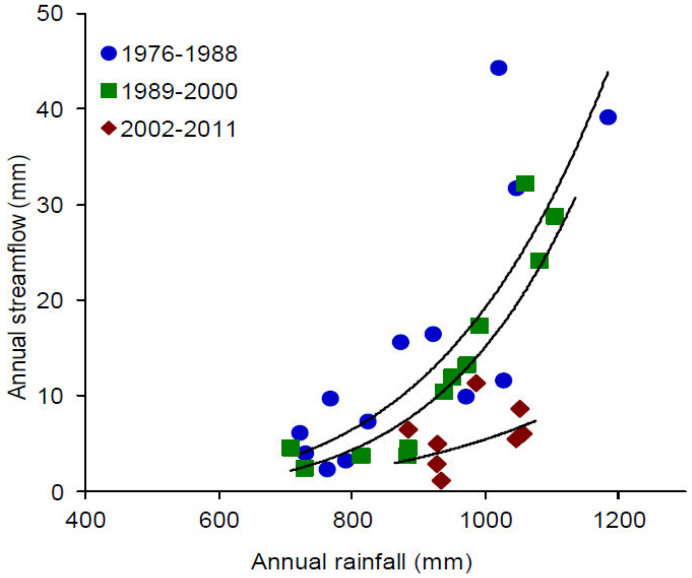
Kuczera (1985, cited in Vertessy *et. al*. 1998) developed an idealised curve describing the relationship between mean annual streamflow and forest age for mountain ash forest in Victoria. This shows that after burning and regeneration the mean annual runoff reduces rapidly by more than 50% after which runoff slowly increases along with forest age, taking some 150 years to fully recover.



Kuczera (1985) Curve.

In the western Australian catchments Bari and Ruprecht (2003) found logging and thinning led to increases in runoff for 10-15 or more years, with maximum increases ranging from 5 to 19% of mean annual rainfall, depending on the level of reduction of vegetation cover and catchment characteristics. As indicated by the trends, stream flows are likely to have continued to decline because of the increasing evapotranspiration of the regrowth.

From the late 1990's to 2001 there has been a major drop in streamflows into Perth's dams (Petrone *et. al.* 2010, Kinal and Stoneman 2012) which has been attributed to a disconnect between groundwater and stream flows. Kinal and Stoneman (2012) identified that from 1976 to 2011 the groundwater system progressively declined and disconnected from the surface water system around 2001, causing the proportion of rainfall that became runoff to drop by an average 50%. This had the benefit of reducing the runoff of saline groundwater, though contributed to a growing water supply crisis.



From Kinal and Stoneman (2012): Annual streamflow in relation to annual rainfall. Note the reducing runoff (streamflow) to rainfall relationship.

Petrone *et. al.* (2010) assessed runoff on the Darling Plateau into Perth's water supply dams, finding that from 1989–2008 there was no significant trend in annual rainfall, "*however, the majority of reservoir inflow (7 of 9) and streamflow (13 of 18) records showed significant negative trends ... The rate of streamflow decline was greater in the last twenty year period than over the long-term record and ranged from −1.6 to −20.0 mm* yr^{-1}". There was also a significant negative shift in runoff following the particularly dry year in 2001.

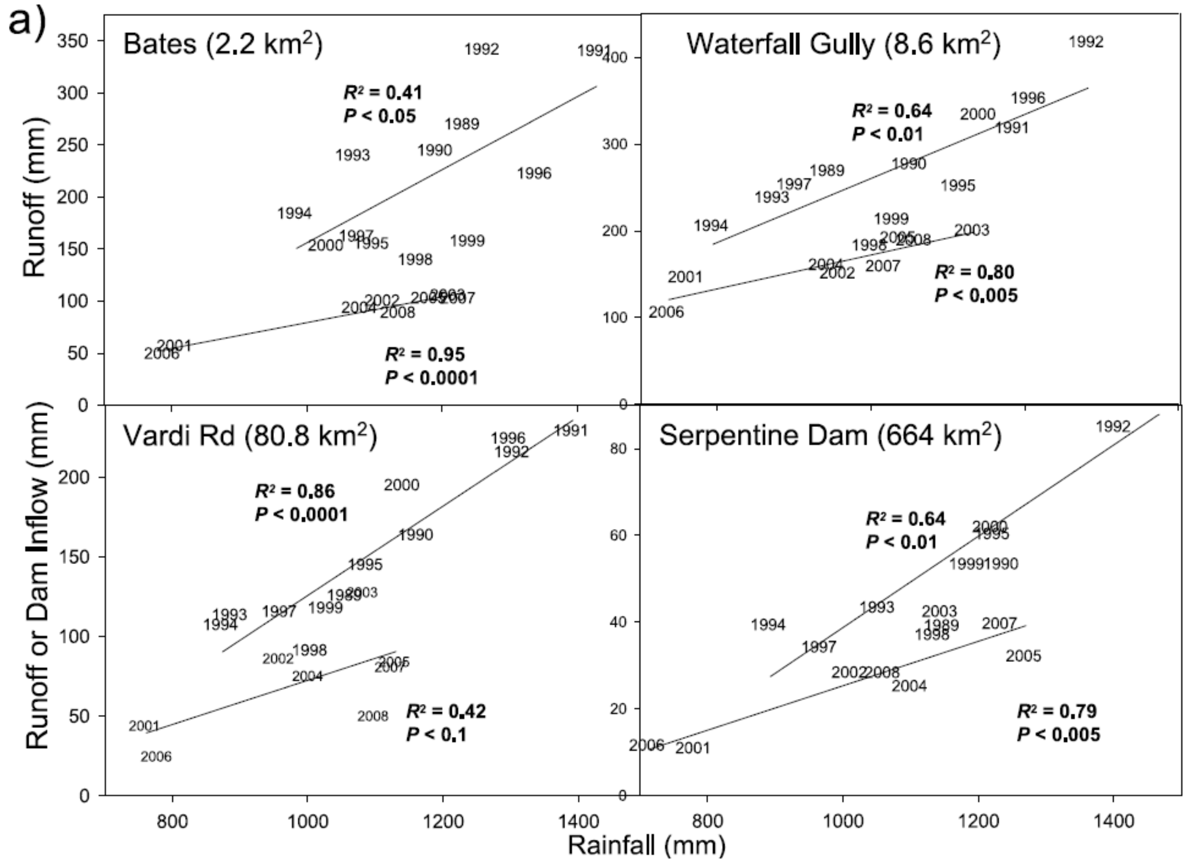


Figure 3. (a) from Petrone *et. al.* (2010): Relationship between annual rainfall and runoff for the Bates, Waterfall Gully and Vardi Rd catchments and the Serpentine dam. Regression lines represent the 1989–2000 and 2001–2008 periods. Note the significant reduction in the volume of runoff for a given rainfall since 2001.

Petrone *et. al.* (2010) hypothesise that when evapotranspiration is in excess of precipitation during a low rainfall year it would create a deficit in soil moisture storage that is carried into the following year, progressively reducing groundwater reserves over years and thus the ability to generate runoff:

> *In our study, a decline in soil moisture and groundwater levels in the last decade may be driving the decline in the proportion of rainfall that becomes runoff. Furthermore, groundwater surface water connectivity that is crucial in maintaining baseflow has likely uncoupled in several catchments that now cease to flow in the summer months. We found that perennial streams are now less common in drinking water catchments, and further stream drying may modify the assemblage of stream biota [Boulton, 2003] and influence the succession of riparian vegetation [Naiman and Decamps, 1997].*
>
> *... Shifts in flow distribution for native forest streams are likely related to falling groundwater levels and loss of groundwater-surface water connectivity, contributing to lower annual*

> *runoff. Current declines in catchment runoff and reservoir inflows have important implications for future water supply as well as the ecological function of aquatic ecosystems.*

As most of Perth's dam catchments are managed for timber production (or have been in the past), or Bauxite mining, the conversion of the forest to regrowth undoubtedly is a major contributor to the declining runoff. In their review of south-west Australian forest silviculture, Burrows *et. al.* (2011) comment on the parlous state of the remaining forests:

> *Reduced rainfall together with high water use in heavily stocked regrowth forests is resulting in little or no runoff, significantly reduced environmental water and increasing incidence of drought deaths. More than 100 years of timber harvesting has altered the forest structure such that today there is a higher density of trees in the smaller size classes over a larger area. There is some evidence that older, relatively even-aged regrowth stands use more water than the old growth forests they replaced.*
>
> *...*
>
> *Where concerns once focused on issues of salinity and Phytophthora infestation due to rising water tables, they have now shifted to the potential for ecosystem collapse, or more likely disappearance, as the water tables have disconnected from the streams, leaving riparian and aquatic communities waterless. There is a potable water need, a forest health and productivity need, and a biodiversity need to manage water balance in these forests.*

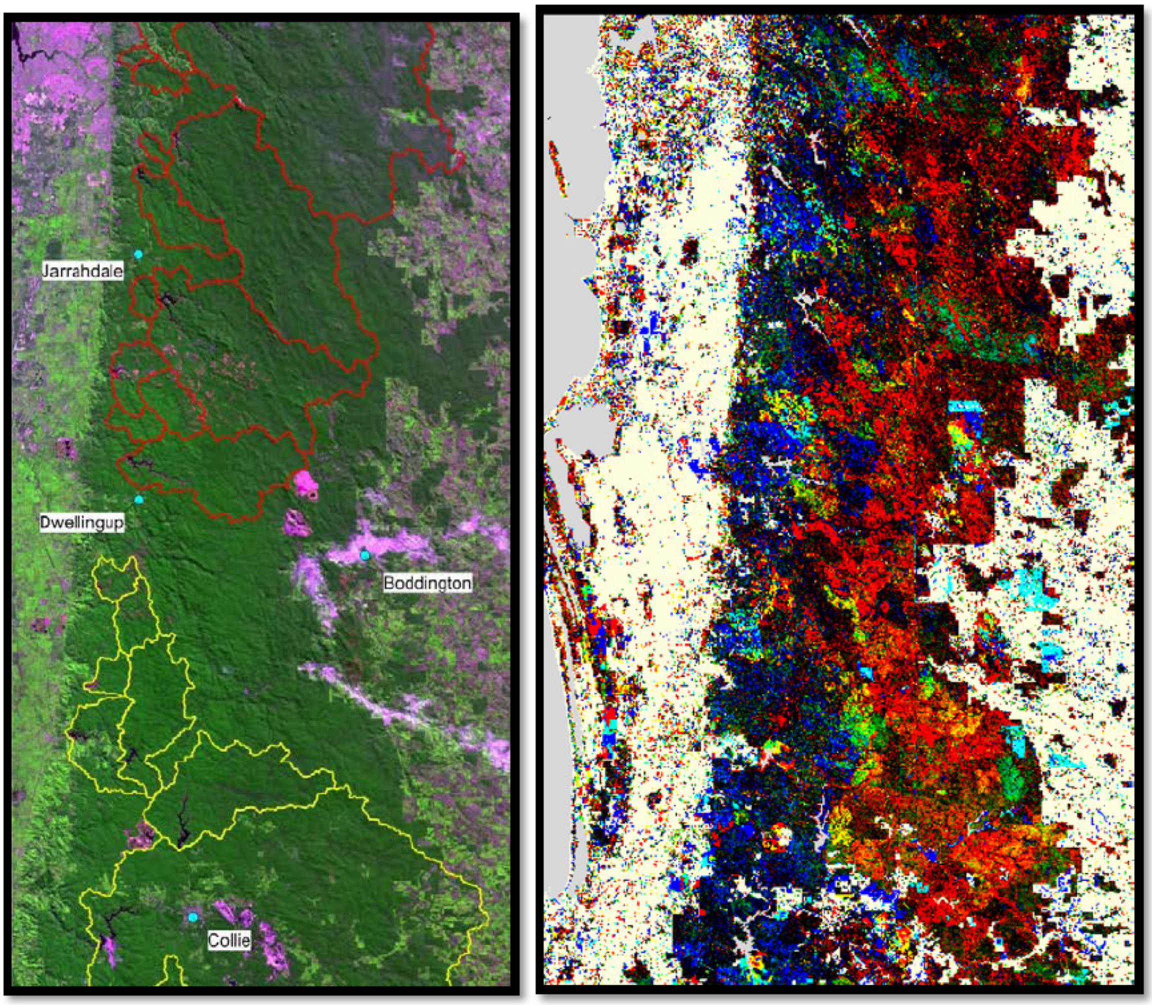
As with most of Perth's water supply catchments, the vast majority of the 664km^2 catchment of the Serpentine Dam is public land managed for logging (Department of Water 2007). It is strange, to say the least, that the management plan for the Serpentine Dam Catchment Area (Department of Water 2007) recognises that runoff into the dam has declined but makes no connection between this and the increased transpiration of the logging regrowth, instead solely focussing on water quality issues while ignoring water quantity issues. Similarly Petrone *et. al.* (2010) managed to ignore the 'elephant in the room' that is logging's effect on transpiration.

This disconnect was not apparent when it came to justifying more logging of the catchments. Amidst great fanfare, in 2005 the Western Australian Government announced its $20million Wungong Catchment Research Project which was meant to herald the delivery of 40 billion litres (gigalitres) of extra water a year to Perth's reservoirs by thinning regrowth. The 12 year 'trial' was meant to cover 7,900ha. The 'trial' was terminated in 2013 after thinning 1,800 hectares of the Wungong catchment. It found that in some years there could be an increase in runoff , though in years of poor rainfall "*particularly in years 2006, 2010 and 2012, there was no measurable increase in streamflow at the dam as a result of catchment management*" (Water Corporation, 2017). Given the failure of this 'trial' it is not surprising that the monitoring was stopped early and that no details of the outcomes were found online. It appears that the initial increase in runoff was short lived and the subsequent decline in runoff seems to have been quicker than that identified by Bari and Ruprecht (2003).

Despite the failure of the on-ground trials, and the curtailing of monitoring, the Government has pursued the idea of reducing the "Leaf Area Index" (LAI) of the forest by thinning. Modelling has been used based on Landsat images that identify surrogates (of questionable veracity) for LAI. These have confirmed the over-riding importance of vegetation structure in determining runoff.

Li *et. al.* (2010) analysed forest and catchment data from the southwest region spanning nineteen years to estimate effects of forest density on runoff and to predict changes in runoff associated with forest management and rainfall scenarios. As a surrogate measure for forest density and disturbance they relied upon a simple spectral index over a time series of Landsat TM imagery to identify vegetation changes (ForestIndex). As well as this surrogate they included topographical variables and a host of rainfall variables. They used the rainfall-runoff ratio to identify the relative significance of variables, concluding that (aside from location) 'ForestIndex' was the most significant variable to explain changes in runoff, noting:

> *... that higher vegetation cover as indicated by ForestIndex is generally negatively associated with [rainfall-runoff ratio]. This is in accord with the common understanding that more vegetation leads to higher water consumption and less water yield.*



LEFT: Figure 2 from Croton *et. al* (2013); Northern jarrah forest water-supply catchments (red and yellow outlines) within the Integrated Water Supply System (IWSS). RIGHT: Figure 5 from Li et. al. (2010): Cover trends image 1989-2007 for perennial vegetation south-east of Perth (100x160km). Red indicates linear decline in cover index; blue linear cover index increase. Green, yellow and cyan indicate curvature in the response over time. Black areas are more stable. Note the widespread forest decline (red) in the eastern part of the forest area, apparently showing ecosystem collapse and indicating a possible breakdown of the inland transport processes for atmospheric moisture.

Croton *et. al.* (2013) confirmed that "*when the present hydrology of the northern jarrah forest is assessed, it is a system where soil-water storages, groundwater levels and streamflows have declined from historical levels, and left to its own devices they are likely to decline further*". They concluded from their modelling of LAI and future climate change "*if the CSIRO Mk 3.5 climate scenario were to occur in the absence of major reductions in LAI, then all streamflow within the* *northern jarrah forest would disappear by 2070, and even by 2050 the majority of the northern jarrah forest would be producing no streamflow*"..

Croton *et. al.* (2013)'s solution is to undertake radical and frequent thinning of vast tracts of the higher rainfall areas to reduce LAI (and thereby evapotranspiration) with the hope of increasing runoff. This approach is likely to be driven by timber production objectives. Aside from their Wungong experiment proving this doesn't necessarily work, this is being proposed with no consideration of the consequences that reduced evaporative cooling, atmospheric moisture and cloud cover will have on the already tenuous hydrological cycle. They should know better by now.

It is evident that south-west Australia has an ongoing water crisis largely of their own making. Deforestation has the effect of lowering rainfall, raising watertables, and causing salinisation. Logging, and mining rehabilitation, has the effect of increasing evapotranspiration and lowering watertables. The vegetation obviously had the balance between these divergent influences 'just right', until it was irrevocably destroyed by the heavy-handed and ill-informed approach to native vegetation practiced over the past 200 years. What is most worrying is that vegetation management in Western Australia still appears to be driven by mining and logging interests, while inconvenient studies and facts are ignored. While ever this continues the Western Australian climate will continue to degrade.

While global warming is real and is contributing to Western Australia's deteriorating climate, which will increase in magnitude over time, other causes such as those relating to deforestation and vegetation degradation are being swept under the cover of CO^2 induced climate change.

The experience in south-western Australia is being repeated around Australia, with the Murray-Darling basin also in an advance state of decline. It is apparent that clearing of native vegetation, and changes to vegetation structure resulting from grazing and logging practices, are having profound impacts on rainfall and runoff around the south and east of Australia. It is urgent that we remove the blinkers, not be dictated to by vested interests, and learn from these experiences. We need to actively seek to halt and reverse the decline. The Western Australian experience is that once tipping points are reached it is not easy, and may prove impossible, to repair the damage.

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Koala density, habitat, conservation, and response to logging in eucalyptus forest; a review and critical evaluation of call monitoring

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ABSTRACT

This study is the second in a series that examines the habitat requirements and response to logging of koalas (*Phascolarctos cinereus*) inhabiting tall eucalypt forests of north-east NSW. It presents the findings of koala population and habitat monitoring surveys in Pine Creek State Forest and Bongil Bongil National Park using a combination of call-counting and direct observation (spotlighting). The 6400 ha study area was mapped into 6 zones of increasing koala habitat quality by ground survey of forest structure and floristics on a 200 m grid. The accuracy of habitat definition and mapping was tested by stratified transect counts of koala calls and sightings over two consecutive years (1997–98). Average koala density increased steeply and significantly, from 0.02 – 0.20 koalas/hectare, with increasing mapped habitat quality based on increasing forest age, structural complexity, local food tree species diversity, history of prior koala occurrence and decreased past logging intensity. This relationship was driven primarily by breeding females, with the number of male koala calls weakly or uncorrelated with koala sightings and mapped habitat quality. Male koalas were more widely and uniformly distributed than females, including areas of low quality, plantation, and intensively logged forest. This finding explains the discrepancy between our results and those of other recent studies which concluded that koalas are tolerant of intensive logging based on modelling of calling male koalas and reliance on an untested assumption that male calling is indicative of female breeding success. Koala density in a subset of the highest quality habitat was relatively stable at 0.28 koalas/ha (3 hectares/koala) over the long term (1997–98 and 2012–2023). Key characteristics of the forest koala population, including low stable density, large home ranges, preference for high food tree diversity and locally unique food trees (including *Allocasuarina torulosa* and *Syncarpia glomulifera*), are not adequately explained by existing koala habitat models.

We present a new paradigm to explain regional variation in koala distribution, habitat and foraging preferences based on variations in foliage chemistry (toxicity and nutritional value) determined by the duration and stability of local plant-koala interactions in response to past fire, hunting, predation and logging disturbance history. We hypothesize that koala density in stable forest populations is regulated at low levels by a combination of selected and induced increases in leaf toxicity and decreases in leaf nutrition that limit koala browsing to benign levels of about 1-2% of annual leaf production. Large home ranges, complex mature forest structure, high food tree diversity and a specialized or diverse gut microbiome may be essential to allow females to rotate and change food trees frequently to minimize induced toxicity and select individual leaves with sufficient nutrients to support breeding and lactation with minimal risk of predation. High density koala populations (> 0.6/ha) occur primarily in areas where koalas have been introduced or re-introduced to planted habitats and natural areas where aboriginal hunters and dingoes were historically present but are now absent, and where food trees have not been selected for resistance to koala browsing pressure.

Key words: koala, habitat, density, folivore, logging, GIS models, song meters, predation.

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INTRODUCTION

The koala (*Phascolarctos cinereus*) was recently (DAWE 2022) classified as endangered and is one of more than 100 mammal species considered vulnerable, endangered, critically endangered, or extinct in mainland Australia under the Environment Protection and Biodiversity Conservation Act 1999. Australian native mammals have undergone a greater level of extinction and decline than those on any other continent (Short and Smith 1994; Woinarski *et al.* 2015), and the most affected species have been ground-dwelling mammals susceptible to hyper-predation by dogs (*Canis familiaris*), introduced European red foxes (*Vulpes vulpes*) and feral cats (*Felis catus*) in regions where predator abundance has been greatly elevated by fast breeding introduced rabbits (*Oryctolagus cuniculus*), mice (*Mus musculus*) or native rodents in the genus *Rattus* (Smith and Quin 1996; A.P. Smith unpublished). Only six arboreal mammal species are listed as threatened, and the most common cause of decline in this group is loss of tree hollows (used for shelter and reproduction) in timber production forests where intensive logging or clear-fell harvesting has replaced structurally complex old growth forests with young, uniform-aged regrowth harvested on rotations too short for replacement hollows to develop (Smith 1982; Smith and Lindemayer 1988; Eyre and Smith 1997; Smith 2010, 2019). The koala does not depend on tree hollows but sleeps in the open which reduces its susceptibility to old growth logging but increases its susceptibility to wildfire (Lunney and Leary 1988, Lunney *et al*. 2004), hunting (Warneke 1978), predation by dogs (Smith 2004; Allen *et al.* 2016) in the more open forests and woodlands where koalas come to the ground to move between trees, and exposure to high and low temperatures and evaporative water loss during droughts (Gordon *et al.* 1988; Rowland *et al*. 2017).

Prior to European settlement, the koala would have been an easy target for Aboriginal hunters and dingoes in frequently burnt grassy open forests and woodlands and is likely to have been eliminated or reduced to rarity in habitats in well populated coastal, inland and riverine areas. Domestic dogs can locate koalas in trees by smell, and trained sniffer dogs are now used to locate koalas in surveys (Cristescu *et al.* 2015). Koalas were not recorded by early explorers (Oxley and Mitchell) in open forest and woodlands on the northern inland slopes of the Great Dividing Range in NSW, and sightings were few until the population expanded rapidly in the vicinity of Gunnedah after about 1970 (Smith 1992; Ellis *et al*. 2016). Similarly, in Victoria koalas were scarce or absent from inland low elevation forests and woodlands prior to European settlement and largely confined to tall open forests of the Eastern Highlands (Warneke 1978). There are no records of koalas from 1850s mammal surveys carried out in riverine and open forests in western Victoria and the Murray River system prior to the spread of pastoralism and the introduction of rabbits and foxes (Menkhorst 2009). However, koalas were reported by pioneer settlers (Committee of the South Gippsland Pioneers Association 1920) to be abundant in tall, dense, wet forests in the ranges and foothills to the east of Melbourne where Aboriginal tribes were sparse or absent. Firsthand accounts of the "big timber" and "scrub" clearing in South Gippsland at the time of settlement in the 1870s describe native bears as being numerous, with up to 6 individuals to be seen at one time in tall, giant gum trees (*Eucalyptus globulus* and *E. rubida*), "*more than 100 foot up without a branch to rest on*" (Elms 1920). Today this pattern is reversed, koalas are scarce or absent from tall wet forests of the Victorian Highlands and only locally abundant in dispersed low elevation woodlands and low open forests where they have been mostly introduced or re-introduced (Menkhorst 1995; Whisson *et al.* 2016).

It has been claimed that koalas prefer woodland and low open forest habitat (Lee and Carrick 1989) where they attain high densities and are easily studied, but this preference may be an artifact of post-European expansion following the cessation of Aboriginal hunting and exclusion of dingoes or wild dogs from much of the koala's geographic range by fencing, baiting and bounty hunting. The anatomy of the koala has been described as suited to movement by leaping from tree to tree (Strahan 1978) rather than coming to the ground, suggesting that the ancestral habitat of the koala may have been taller forests with more closely spaced trees rather than dry open forests and woodlands where predation risk was high. Remnant tall forests are widespread along the Great Dividing Range of eastern Australia from Victoria to southern Queensland in a network of scattered National Parks embedded within a matrix of State Forests managed for wood production. Today, koalas are sparse or absent from large tracts of these forests and continue to decline across most of their geographic range, especially in areas that have been fragmented, burnt, or logged (McAlpine *et al.* 2015). Extensive surveys of tall open forests conducted for logging impact studies in northern NSW during the 1990s found koalas to occur at less than 2% of survey sites in the Glen Innes, Tenterfield and Walcha-Nundle-Styx River Forest Management Areas on the Northern Tablelands and at less than 9% of sites in the Grafton, Casino, Coffs Harbour and Urunga Forest Management Areas on the mid north coast (Smith *et al.* 1992, 1994, 1995). Koalas were only abundant (40% of sites) in lower elevation parts of the Urbenville and Murwillumbah Forest Management Areas, close to the Queensland border, in areas with a history of low intensity logging that retained mature and structurally complex multi-aged forest (Andrews *et al.* 1995). In a more recent study Law *et al*. (2018) reported higher koala occupancy rates (62%) using song meters deployed for 7-14 days across northeast NSW forests, but this study specifically targeted known koala high use areas and medium to high quality habitat only. It also recorded male occupancy which, as shown in this study, may include extensive areas of habitat unsuitable for breeding female koalas. In southeast NSW forests, koala populations declined after European hunting for hides, burning and clearing for agriculture early last century (Lunney and Moon 2012) and more recently after clear-fell harvesting for woodchip (compounded by the effects of drought and warming) and have since remained scarce (Lunney and Leary 1988; Lunney *et al.* 2014).

Detailed ecological studies of koalas in tall wet forests are few and largely limited to radiotracking and scat surveys in the Pine Creek State Forest and Bongil Bongil National Park region of northern NSW (Smith and Andrews 1997; Smith 2004; AMBS 2011; Radford Miller 2012), and modelled associations between koala survey records and environmental variables across a broad range of forested regions (Lunney 1987; Smith *et al.* 1992, 1994, 1995; Andrews *et al.* 1995; Kavanagh *et al.* 1995; Law *et al.* 2017, 2022a; Goldingay *et al.* 2022). Scat surveys in the Pine Creek State Forest found koalas to prefer floristically diverse and structurally complex multi-aged forests in areas of high site quality with a high stocking of larger trees, an abundance of preferred koala food trees (KFT), and no recent intensive logging (Smith and Andrews 1997; Smith 2004; Radford Miller 2012).

Despite these findings and the apparent preference of koalas for larger trees in many landscapes (Hindell and Lee 1987; Lunney *et al.* 2000; Phillips and Callaghan 2000; Moore and Foley 2005; Matthews *et al.* 2007; Ellis *et al.* 2009), the threat to koalas from intensive timber harvesting in tall productive forests appears to have been investigated and largely dismissed in conservation planning and management. The NSW Government Koala Strategy (Department of Planning and Environment 2022) called for "*research into koala response to intensive harvesting in active forests*" by the NSW Natural Resources Commission (NRC) to "*deliver an independent research project to better understand how koalas are responding to intensive harvesting on the NSW North Coast*". Following delivery of research projects undertaken by the Department of Primary Industries Forest Science Unit and others, the NSW National Resources Commission (NRC 2021, 2022) claimed that "*emerging evidence to date suggests intensive harvesting occurring in the past five to 10 years is unlikely to have impacted koala density, but more research is needed on the immediate responses*". The National Recovery Plan for the koala (DAWE 2022) did not consider the need for more research or recognize timber harvesting as a significant threat, noting in the section on threats from native forestry that "*Between 2015 and 2017, the NSW Department of Primary Industries forests scientists undertook a large-scale study on Koala occupancy in the forests of north-east New South Wales, including the response of koala to timber harvesting. Koala occupancy was not influenced by timber harvesting intensity, time since harvesting, land tenure, landscape harvesting extent or old growth forest extent (Law et al. 2018)*". This conclusion is based on the results of studies by Law *et al.* (2018, 2022a, b) reported in NRC (2021, 2022) which used remote call monitors or autonomous recording units (ARUs) to record and identify male koala calls and model male calling frequency as a function of mapped environmental variables and logging history in NSW timber production forests.

These studies relied on an untested assumption that male and female koalas have similar habitat requirements and a similar response to logging. Law *et al.* (2018) justified reliance on male calls as an indicator of koala habitat quality based on an argument that male koala bellowing serves to avoid males and attract females, and therefore that "*an increase in bellow rate likely reflects an increase in breeding activity in a population*". The acoustic monitoring studies of Law *et al.* (2018, 2022b) failed to detect any adverse impacts of timber harvesting on (male) koala populations, leading the authors to claim that "*native forestry regulations provided sufficient habitat for koalas to maintain their density, both immediately after selective harvesting and 5–10 years after heavy harvesting*". In NSW the Coastal Integrated Forestry Operations Approval (Coastal IFOA) allows clear-felling (clearing of all trees and ground disturbance) in Blackbutt Forests and intensive logging (retention of only 10-12 m^2 / hectare tree basal area) in remaining state forests (NRC 2022). This level of tree basal area retention after logging is much lower than levels of about 23 – 28 m^2/ha that remained after earlier selective logging operations during the 1970s–90s (Smith 2001/2010). The results of the Law *et al.* (2018) acoustic modelling and logging impact surveys that support this or higher intensity logging of koala habitat are inconsistent with the findings of earlier studies (Andrews *et al.* 1995; Smith and Andrews 1997; Smith 1997, 2004) which predicted that high intensity (clear-fell) logging and increased intensity selective logging of the type permitted under the Coastal IFOA is likely to either eliminate or significantly reduce breeding female koala populations in logged forests.

The current study provided an opportunity to test whether the habitat requirements and response to logging differ between male and female koalas by undertaking simultaneous counts of male and female koalas and male call counts along a gradient of increasing koala habitat quality and decreasing logging intensity. The primary purpose of the study was, however, much broader and aimed to: a) provide an independent test and validation of the key findings and predictions of earlier koala habitat and logging impact studies in the study area (Smith and Andrews 2001; Smith 1997, 2004); b) test the accuracy of koala habitat mapping prepared for the Forestry Commission of NSW 2002 Koala Plan of Management covering the study area; c) measure koala population stability in the study area by analysis of long term monitoring data (1996–1998 and 2012–2022); and d) develop an improved definition of koala habitat for koala conservation and management in natural forest that explains all the unique characteristics of the koala population in the study area. These characteristics include its stable, low density, sex differences in distribution, female preference for structurally complex and relatively undisturbed forest with a high diversity of preferred food tree species, and utilization of non-eucalyptus food trees including *Allocasuarina* and *Syncarpia*. These characteristics are not adequately explained by existing koala habitat models, especially those that rely on lists of so-called primary and secondary koala food trees, and those generated by identifying correlations between mapped environmental layers (e.g. climate, soils, forest type, recorded land use history) stored in Geographic Information System (GIS) and koala call and sighting location records. This study reviews the density, stability and habitat requirements of natural koala populations, and calls for a new approach to habitat definition for koala conservation that takes into account a much broader and more complex array of variables. These include, in addition to KFT diversity and abundance, the capacity of individual trees to vary levels of foliage toxicity and nutritional value in response to koala browsing, and the extent to which local specialization in koala gut microbiomes may enable stable koala populations to overcome plant defenses and utilize local tree species unpalatable in other regions.

METHODS

Study Area

The 6400-hectare Pine Creek State Forest study area includes portions of both Pine Creek State Forest and the adjacent Bongil Bongil National Park (BBNP) gazetted in 2003, and is located in coastal northern New South Wales (NSW) approximately 18 km south of Coffs Harbour, on undulating to hilly topography up to 160 m elevation (Figure 1). The study area is divided into two portions dissected by the Pacific Highway, and collision with motor vehicles has been identified as a significant threat to koalas in the immediate vicinity of the highway but is not considered a threat elsewhere in the study area

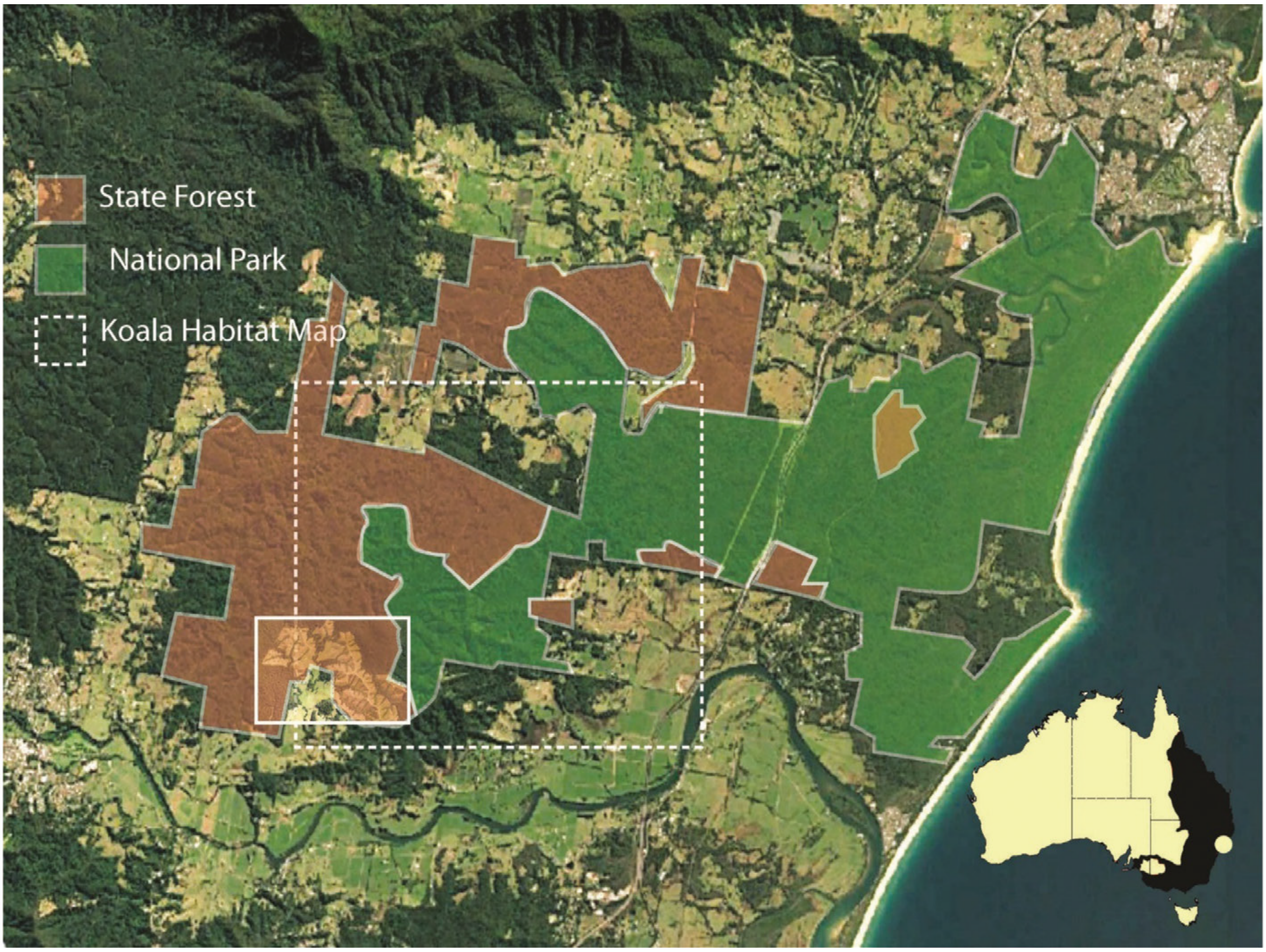

Figure 1. Pine Creek and Bongil Bongil National Park study area (adapted from Google Earth 2023) showing the occurrence of State Forest, National Park, private forest, and forest cover links to the north-west. The large dashed white square identifies a subset of the study area in which koala habitat mapping and the location of transect survey sites are illustrated in Figure 2. The small white square identifies the location of clear-fell timber harvesting undertaken in 2010 and shown in more detail in Figure 3. Inset shows koala distribution (black) in Australia and location of the study area near Coffs Harbour NSW (yellow dot).

(Smith 1997; Lunney *et al.* 2022). Annual rainfall is high (about 1600 mm/annum) and falls year-round but is heavier in summer and lower in winter and early spring. Maximum temperatures are moderate, ranging from mean monthly values of 19 °C in winter to 27 °C in summer (Bureau of Meteorology 2022). Drought and water shortage is not likely to represent the level of threat to koala density reported on the drier margins of its range (Ellis *et al.* 1995). Soils are typically of low to moderate fertility (Milford 1999) but productivity is high, with forests attaining heights of 40-60 m in gullies and on protected aspects. The Pine Creek State Forest has been extensively logged at low to moderate intensity since the late 1800s and comprises a mosaic of floristic types and structures which do not necessarily reflect the original forest distribution (SFNSW 2000). The area supports four major floristic communities: 1) native Plantation Forest in areas clear-felled and replanted with Flooded Gum (*Eucalyptus grandis*), Blackbutt (*Eucalyptus pilularis*) or Blue Gum (*Eucalyptus saligna*) and undergoing varying degrees of naturalization by seeding from surrounding forest; 2) Dry Blackbutt (*E. pilularis*) dominated forest on the ridges and more exposed aspects; 3) Tallowwood (*Eucalyptus microcorys*) and Moist Blackbutt (*E. pilularis*) dominated forest on sheltered aspects and lower slopes; and 4) Moist Hardwood forest dominated by natural Flooded Gum, Tallowwood, Blue Gum, Brush Box (*Lophostemon confertus*) and palms in the moist gullies (Smith and Andrews 1997). Forest Oak (*Allocasuarina torulosa*) and a range of other species including Turpentine (*Syncarpia glomulifera*), Grey Gum (*Eucalyptus propinqua*), White Mahogany (*Eucalyptus acmenoides*), Bloodwood (*Corymbia gummifera*), Red Mahogany (*Eucalyptus resinifera*) and Ironbark (*Eucalyptus siderophloia*) are also widespread, especially in non-plantation forest types. Understorey vegetation is predominantly moist, and a network of rainforest and gully wet sclerophyll forest provides koalas with good shelter from heat and drought and refuge from wildfire.

The study area is largely isolated from other areas of koala habitat by the Bellinger River to the south, the Pacific Highway and coast to the east, and cleared land to the north and west except for two narrow forest corridors about 400-700 m wide that link with more extensive forests along the Great Dividing Range to the northwest across areas of private land (Figure 1). The study area supports one of the largest known regional koala populations in NSW, comprising about 400 individuals (Smith 1997), and has a higher density of koalas than any other arboreal marsupials. It is located within the proposed Great Koala National Park, a plan by the National Parks Association of NSW and affiliated organizations to protect 315,000 hectares of high-density koala habitat in northern NSW by linking 140,000 hectares of existing National Parks with 175,000 hectares of surrounding State Forest. The NSW government (Department of Planning and Environment) has recently announced a process to establish the Great Koala National Park and to halt timber harvesting operations in the 106 koala hubs within the area being assessed for the park (www.environment.nsw.gov.au).

Logging and Koala Research History

The Pine Creek State Forest has a long history of timber harvesting since the late 1800s (Newman and Partners 1997). Early harvesting concentrated on selective removal of large, good quality stems from a small number of merchantable species within rainforests along gullies which were soon exhausted. By 1969 many of the previously cleared and logged rainforest gullies had been regenerated by sowing or planting with Flooded Gum, giving rise to "plantation like" young regrowth forests with a relatively uniform structure and a predominance of stems under 40 cm diameter. In recent years these forests have undergone naturalization to varying degrees following seedling establishment from surrounding native forest, especially by shade tolerant Tallowwoods and Grey Gums preferred by koalas. The surrounding natural forest and intervening areas were subject to small patch harvesting and Timber Stand Improvement (TSI) to remove large, old senescent trees (with many large hollows) and reduce competition from logging regrowth. During the 1970s and 1980s harvesting was more selective and large mature trees deemed capable of further growth were retained to provide sawlogs in subsequent cutting cycles (SFNSW 2000). In 1994 intensive large gap clear-felling that removed all standing trees, irrespective of size and economic value, recommenced in the Pine Creek State Forest, and in 1995 the National Parks and Wildlife Service (NPWS) withdrew logging consent after the local community voiced concerns about the impact of clear-fell harvesting on the local koala population (Smith 2004). A committee including representatives of the community, State Forests of NSW (SFNSW), NPWS, timber industry, and conservation groups was formed to oversee preparation of a koala plan of management for Pine Creek State Forest. A scientific study of koala habitat requirements and response to timber harvesting was funded and undertaken in 1996-97 (Smith 1997; Smith and Andrews 1997; Smith 2004), and the resulting findings and recommendations (Florence *et al.* 1997) were considered in preparation of a koala plan of management for the region by SFNSW (2000). Significant positive correlations were found between koala density and a range of environmental variables including the abundance of locally preferred koala food tree species (Tallowwood, Grey Gum, Flooded Gum, Blue Gum, White Mahogany, Blackbutt, Swamp Mahogany (*Eucalyptus robusta*), Forest Red Gum (*Eucalyptus tereticornis*) and

Forest Oak), koala food tree species richness, the abundance and basal area of mature trees (50–80 cm diameter), forest structural complexity, soil type and fertility, and distance away from "plantation" forest.

The study concluded that koala conservation in the Pine Creek State Forest was inconsistent with clear-felling and high intensity logging that produced low diversity forests with uniform regrowth structure. It recommended that koala habitat in the Pine Creek State Forest be mapped and zoned into areas of increasing koala habitat quality and decreasing harvesting intensity for koala conservation and management (Florence *et al.* 1997; Smith 1997). Koala habitat across the Pine Creek State Forest was subsequently mapped by the Coffs Harbour Pine Creek Koala Support Group under contract to the NSW Government, and the resulting map (Figure 2) provided a foundation for the koala management plan prepared by SFNSW (2000). The findings of Smith and Andrews (1997) were tested and validated in part by a postgraduate study of koalas by radio-tracking, spotlighting and diet analysis throughout the Pine Creek State Forest between 1999 and 2002 by Radford Miller (2012), who concluded that "*the uneven-aged, species-rich, koala feed tree-rich zones, including the zone based largely on the presence of prior koala records, did indeed have the highest estimated koala densities*". Koala habitat was classified into 6 management zones with increasing ratios of conservation to wood production emphasis. The lowest quality, predominantly plantation, habitat in the Pine Creek State Forest was zoned for "*wood production emphasis*" but with an overall objective to "*maintain the distribution and abundance of koalas*". The highest quality habitat was zoned for "*koala emphasis*" with an objective to "*enhance the distribution and abundance of koalas as a potential source population for surrounding areas and addition to the interim reserve.*"

Intensive logging in the Pine Creek State Forest recommenced in 2001 with little consideration to these management plan objectives and in response to subsequent community concerns just under half of the Pine Creek State Forest was added to Bongil Bongil National Park in 2003 (Smith 2004). In about 2006, clear-felling of the lowest quality forests commenced in the remaining Pine Creek State Forest and by 2011 about 1500 hectares had been cleared and replanted with high wood value species including Blackbutt (Figure 3a). An aerial photograph of the southwest portion of the Pine Creek State Forest in 2010 (Figure 3b) shows approximately 200 ha of clear-felled forest on either side of a 1333 m survey transect (TB 6) where one koala was seen and five koalas were heard in 1998, and an estimated population of about 15 koalas was present. In 2012, the Pine Creek State Forest Koala Plan of Management was suspended and clear-felling continued. In 2022, the NSW NRC endorsed an expansion of the large gap clear-felling of the type shown in Figure 3 and carried out in former plantation forest of the Pine Creek State Forest to more extensive regions of native forest in northern NSW.

Koala Habitat Mapping

In 1997 koala habitat in the Pine Creek State Forest was mapped using Geographic Information Systems (GIS), after the methods of Ferrier and Smith (1992), Smith *et al.* (1997) and Smith *et al.* (2002), to interpolate and extrapolate the predictions of modelled statistical associations between koala records and mapped environmental variables. Only a limited number of indirect mapped environmental variables (topography, geology, forest type, soil type and compartment logging history) could be used in this process because no maps were available for the most important predictor variables (abundance of locally preferred koala food trees (KFTS), koala food tree species richness, and forest structural complexity). Consequently, the resultant maps, although significant, when tested against actual koala distribution determined by spotlighting surveys, explained only a small portion of the total variability in koala distribution and abundance. These initial GIS-generated habitat maps were considered suitable only for predicting extreme differences between plantation and non-plantation forest and lacked the accuracy necessary to predict and map variations in koala distribution and density within areas of more natural, non-plantation forest. SFNSW forest type maps, based on aerial photograph interpretation (API) of Baur (1965) forest types, were not found to be useful for koala habitat mapping because no significant correlation was found between koala distribution or KFTS abundance and mapped forest type (Smith and Andrews 1997; Smith 2004).

Limitations of koala habitat modelling and mapping using GIS and mapped attributes in the Pine Creek State Forest were subsequently addressed by carrying out ground surveys of preferred koala floristic and structural attributes (identified by Smith and Andrews 1997) throughout most of the forest on a 200 m grid. Each grid square was classified and mapped into one of 5 increasing habitat suitability classes by engineering surveyors, John Pile and John Murray, on behalf of the Coffs Harbour Pine Creek Koala Support Group in 1997. This mapping was endorsed by the Scientific Working Group (Florence *et al.* 1997) responsible for advising on koala management and was subsequently incorporated, with some amalgamations and boundary adjustments, into 6 management zones that provided a foundation for the SFNSW (2000) Pine Creek State Forest Koala Plan of Management. Zones 1- 4 reflected a gradient of increasing habitat suitability based on increasing forest structure (tree size and density), increasing floristic diversity, increasing site quality and decreasing past logging intensity

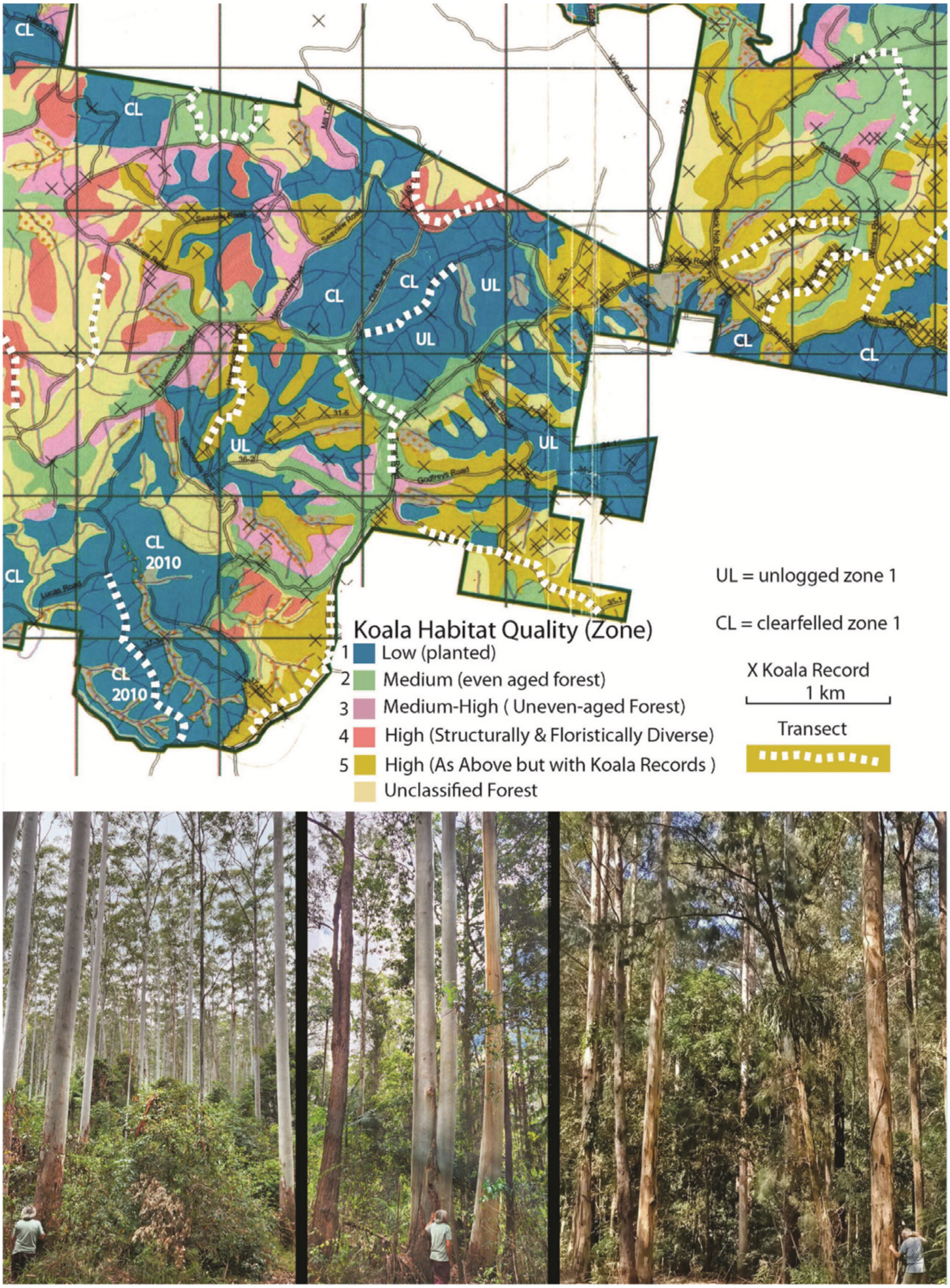

Figure 2. Top. A sample region from the study area showing koala habitat quality mapping (after SFNSW 2000) ranked on a scale of 1–5, the location of transects surveyed in 1998 and 1999, and the location of recent (post–2005) clear-fell timber harvesting operations (CL). Bottom. Examples of forest in zone 1 low quality habitat (left), zone 3 medium quality habitat (centre) and zone 5 high quality habitat (right) photographed (J. Pile) in 2023 to show increasing structural complexity along the gradient.

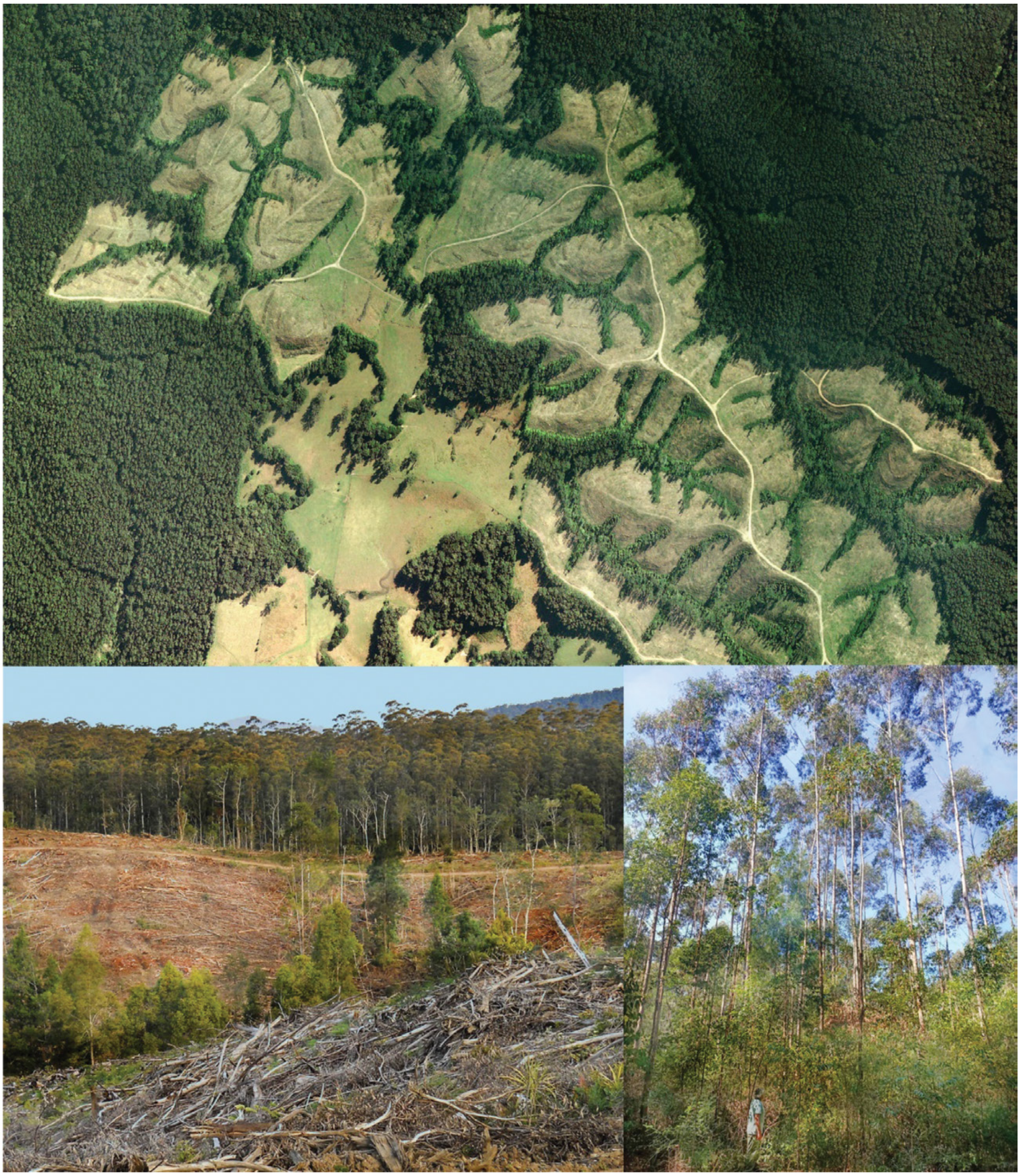

Figure 3. Top, aerial view of a portion of southwest Pine Creek State Forest in 2010 (modified from Google Earth) showing approximately 200 ha of high intensity logging, clear-felled forest on either side of survey transect TB 6 where one koala was seen and five koalas were heard in 1998, representing an estimated density of 0.08 koalas/hectare or a population of about 15 koalas in the cleared area. Lower left, ground view of clear-felling in 2011 and (lower right) ground view of clear felling regrowth in 2023, 12 years later (J. Pile).

(Table 1). Two areas of zone 6 surveyed in this study included unclassified, degraded and partially cleared areas of very low habitat quality and were ranked zero on a habitat quality gradient from 0–5, but elsewhere the quality of zone 6 is variable and may include patches of high quality habitat supporting rare communities like Swamp Mahogany. Habitat in zone 5 was structurally and floristically similar to that in zone 4 but fell within areas identified by members of the local community as koala "hotspots", based on regular koala sightings. A sample of habitat mapping into these 6 zones is reproduced in Figure 2 along with photographs of sample habitats from zones 1, 3 and 5 photographed in 2023. The accuracy of koala habitat mapping for classifying forest structure and floristics in the Pine Creek State Forest was independently

Table 1. Criteria used for classification and mapping of koala habitat into management zones (adapted from SFNSW 2000).

Zone	Forest Structure	Baur 1965 Forest Type in order of predominance	Site Quality	KFTS Species Richness & Stocking #	Koala Hotspots	Area (ha)	Koala Habitat Quality Class^
1	Even-aged Plantation	18 (Plantation)	variable	0–1		1972	1
2	Even-aged Native Forest	37 (Dry Blackbutt) 60 (Mahogany, Ironbark Grey Gum)	Low-medium	0–1		844	2&3
3	Uneven-aged regrowth	37, 36 (Moist Blackbutt) 60	medium	1		706	3A-4
4	Uneven-aged mature & occasional senescent	47 (Tallowwood Blue Gum) 48 (Flooded Gum) 60	high	High (2 or more KFTS)		261	4
5	Uneven-aged mature & occasional senescent	47, 48, 60	high	High (2 or more KFTS)	Known Hot Spot*	950	5
6/0	Variable, uneven-aged to tree-less	Unclassified	variable	variable		868	0–4

* area with a known high density (> 3 per 400 m) of community koala records

koala food tree species (KFTS): tallowwood, grey gum, blue gum, forest oak.

^ after (SFNSW 2002 Appendix 2)

tested between 1999 and 2002 by Radford Miller (2012), who measured forest floristics and structure in sample plots across the region. She found that KFTS species richness varied strongly across the mapped zone gradient (from less than 1 KFTS in zone 1 to 3.5 species in zone 5) and that the basal area of all KFTS increased strongly (more than 10-fold) across zones 1–4. The mean number of tree stems per hectare also increased from zone 1 to zone 5 and stand basal area was lower in zone 1 but relatively constant across zones 2–5. Forest structure in the Pine Creek State Forest has changed in the 23 years since this survey was undertaken, exhibiting a general increase in tree diameter in all unlogged areas and an increase in structural complexity and floristic diversity in unclassified areas and zones 1–2 as these areas have been gradually invaded by non-plantation species.

Koala Survey Methods and Data Analysis

Koala surveys were carried out in 1996, 1998 and 1999 during favourable weather conditions (no strong winds or rain) in the months of October to December on different nights by the same two observers using a walk, listen, spotlight count method. One observer stopped for a 10-minute call listening period every 200 m while the other observer continued walking slowly spotlighting and recording calls between listening stops. In 1996 observers recorded the estimated distance and angle to animals heard and marked call locations on a map where possible to prevent double counting. Calls recorded by both observers from the same koala were identified by triangulation which acted as a check on distance estimation. Faint, distant and poorly discernible calls considered to be more than 200–250+ m away were recorded but not mapped. In 1998/99 distance to calls was estimated in metres. The sex, age (juvenile or adult), tree selection, tree size and behaviour of all animals seen was noted where possible for all animals sighted. Sex determinations were mostly limited to adult females accompanied by dependent young. Surveys commenced between 19.30 and 20.30 hours and finished before midnight. In 1996, surveys were conducted on 20 transects with an average length of 2.23 km at road/track locations randomly distributed across the Pine Creek State Forest. In 1998, 36 survey transects were relocated and specifically stratified to fall within one of six mapped habitat quality classes in the Pine Creek State Forest Koala Plan of Management (SFNSW 2002, Figure 2). Seven transects were located in zones 1, 2 and 3, three in zone 4, 10 in zone 5 and two in zone 6. Transects were slightly variable in length depending on the size of mapped habitat zones and averaged 1.04 km in length and about 75 minutes in survey duration.

In 1999, surveys were repeated at the same locations as in 1998 under similar conditions using the same methods and observers. Survey transects in 1998/99 were by necessity relatively short because they had to fit within patches of the same habitat zone and quality which rarely exceeded 2 km in length. This meant that the effective area surveyed by spotlight on each transect was only about 3.8 hectares which is smaller than average koala home range (about 6 ha female, 25-37 ha male) in the Pine Creek State Forest (AMBS 2011; Radford Miller 2012). Consequently, koala sightings per transect were low, and there was a risk that some koalas were missed by chance on transects with suitable habitat resulting in false absences and a low spread of abundance values for quantitative analysis. To reduce noise caused by this sampling problem, we pooled counts for 1998/99 to give an effective spotlight search area of 7.6 hectares/transect. We also overcame the problem of small sampling area by examining relationships between habitat quality and the frequency of occurrence (presence-absence) of koalas on transects in different mapped habitat zones using logistic regression. The effective survey area per transect for calls was much higher, about 30 hectares. This reduced the risk of recording false absences but increased the risk of recording false positives where koala calls originated from nearby patches of a different quality to that found along the transect or from roaming males passing through unsuitable (non-resident) habitat. Many of the mapped koala habitat zones in the Pine Creek State Forest are small and narrow (200-500 m wide) so that some koala calls are likely to have emanated from adjacent habitats not representative of that along the transect.

For the purpose of analysis mapped koala habitat was considered a continuous variable ranked from zero (in zone 6) to five (zone 5), reflecting a gradient of increasing tree size, cover and floristic diversity and site quality. Associations between koala occurrence and ranked habitat quality (0–5) were analysed by gradient analysis (linear regression, correlation and logistic regression). The data were considered unsuitable for rigorous analysis by comparison of means across mapped habitat categories by ANOVA due to limited replication in zone 6 (2 sites) and zone 4 (3 sites). Linear regressions, correlations and trend line fitting were undertaken using Microsoft Excel and logistic regression analysis was undertaken using modules in the statistical package "Statistica". Critical values of the correlation coefficient were determined from tables in Zar (1984).

Koala Long Term Monitoring in the Pine Creek State Forest

Koala abundance on five 1.5 km long transects located within high quality (zone 5) koala habitat in the Bongil Bongil National Park has been monitored annually by the NSW National Parks and Wildlife Service Coffs Coast Area Staff since 2013 using a consistent method. Transects are surveyed during the mating season (September – October) using a call playback-listen-walk spotlight technique undertaken by supervised volunteer observers. Koala calls are broadcast at four sites spaced at 500 m intervals along each transect. Health, sex and reproductive status (presence of females with young) are recorded where possible. All koalas seen and heard are recorded. Four of the five monitoring transects used by NPWS are located on transects surveyed for this study in 1998/99 and a fifth is close to a transect surveyed in 1998/99 in similar habitat. Koala monitoring data were made available to the authors for the purpose of this study.

RESULTS

Koala Spotlight Counts

Survey effort and the number of koalas observed on walk-listen-spotlight transects during the mating season in 1996, 1998 and 1999 are summarized in Table 2. The number of koalas sighted in 1996 declined rapidly with distance from the transect line and was almost zero beyond 50 m due to increasing obstruction of koalas from view by tall dense forest vegetation (Figure 4). Distances to koalas were estimated rather than accurately measured and exhibited a tendency to heaping caused by rounding of estimates to the nearest 5 or 10 m. A 10 m distance interval was chosen to illustrate patterns of decline and minimize the effect of heaping. Trend lines can be fitted to decline patterns using various statistical algorithms, but most such models have little or no merit for density estimation as they generally assume that density is 100% in the first interval class (Thomas *et al.* 2010). The main value of decline functions is to determine distances for truncating data and to calculate correction factors for comparing counts between forests with markedly different structure and decline patterns. We assumed that koala detection by spotlighting was 100% in the first (10 m) interval class and we used the actual observed decline histogram to truncate koala sighting counts at 50 m and to calculate a correction factor (2.6) to account for animals likely to be present but not seen out to 50 m based on the difference between actual (25) and expected counts (65) assuming expected numbers in each distance interval to be the same as counts in the first interval class (13). Average koala density across all transects was estimated by applying the correction factor of

Table 2. Results of koala call counts and koala sightings 1996–1999.

Survey Year	1996	1998	1999
Sightings			
Total Transect Length (km)	44.50	38.24	38.24
Area surveyed Sightings 100 m strip (ha)	445	382	382
Av. Transect Length (m)	2225	1062	1062
Number of Transects	20	36	36
Survey Date	**15 Oct-30 Dec**	**22 Oct-27 Nov**	**25 Oct-15 Dec**
Av. Survey Duration (min)	144	60	-
Koalas Seen to 50m	25	14	14
Koalas Seen/km. (average per transect)	0.56	0.36	0.37
Koalas seen corrected for detectability (x 2.6)	65	36	36
Density Koalas Seen (koalas/ha)	0.15	0.10	0.10
Calls			
Koalas Heard (inc. faint)	95	89	86
Koalas Heard/km. (Inc faint)	2.1	2.4	2.2
Male Koalas Calling within 150 m	74	63	67
Area Surveyed Calls 300 m strip (ha)	1335	1071	1071
Males Calling /ha	0.055	0.058	0.062
Ratio of All Calls to All Sightings	3.8	6.4	6.1

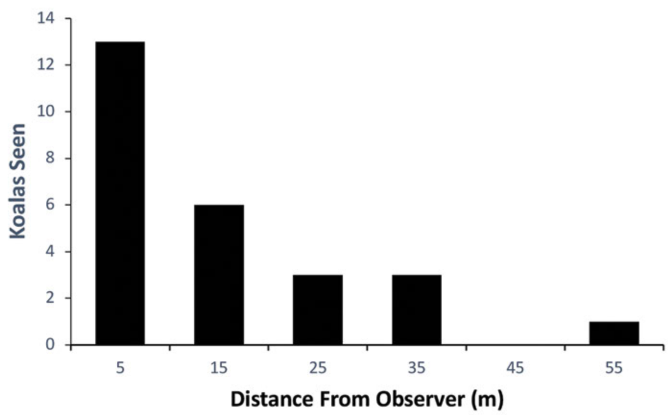

Figure 4. Decline in number of koalas sighted at increasing 10 m distance intervals from the observer in 1996.

2.6 (65/25) to total koala counts out to 50 m either side of the transect line. The observed decline pattern and correction factor was almost identical to that previously reported (Smith and Andrews 1997) for 161 km of vehicle spotlighting undertaken in an independent survey on all roads in the Pine Creek State Forest in 1996/97. Average koala density on all transects was 0.12 animals/ha (8.3 ha per koala) in 1996 and 0.10 animals/ha (9.9 ha per koala) in 1998 and 1999 (Table 2).

Koala Call Counts

The results of koala call counts are summarized in Table 2. On average, koalas were heard 3.8 – 6.4 times more often than they were seen, and one koala was heard for every half kilometre walked or every half hour of survey. The number of calls varied with distance from observer but not as steeply, or in the same manner, as the decline in koala observations with distance. The number of calls recorded within 50 m distance classes from the observer (Figure 5) shows that koalas were less likely to call when observers were nearby (within 50 m). However, the number of calls recorded within the first 50 m right angle distance classes from the transect line (Figure 6) shows that at least some koalas close to the transect line called before or after observers had passed rather than when they were nearby. This response contributed noise to an overall trend of declining koala calls with distance from the observer and rendered the data unreliable or speculative for call density analysis. The general pattern of call decline suggests that all or most calls were heard out to distances of about 150 m after which call detectability fell, reaching low levels at distances over 250 m. Twelve percent of all calls in 1996 and 14% in 1998/99 were classified as "faint",

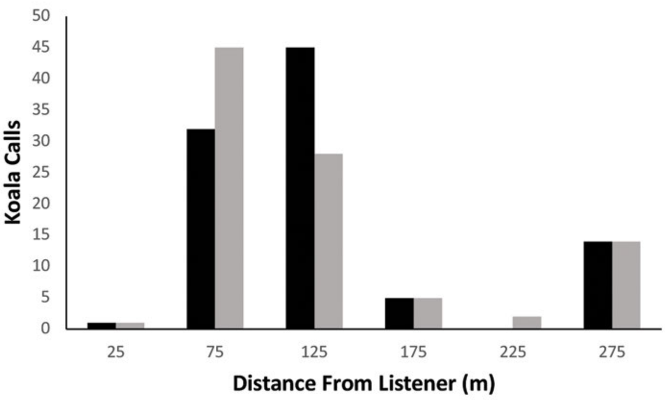

Figure 5. Number of koalas calling in estimated 50 m distance intervals from the listener (grey shading 1996, black 1998).

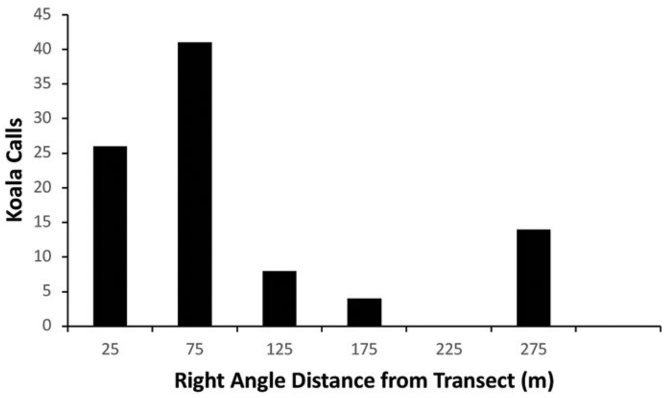

Figure 6. Number of koalas calling in estimated 50 m right angle distance intervals from the transect line in 1996.

or so far away that their distance could not be estimated reliably, and their location could not be triangulated or mapped. Faint calls are included in the largest (275 m) distance class for the purpose of decline analysis (Figures 5,6) but are likely to have included a spread of distances less and greater than 275 m, rather than a cluster as shown. The largest triangulated distance to a call was 249 m.

Koala calls can theoretically be used to estimate male koala density if several key variables are known. Firstly, observers must move forward continuously and triangulate calling animals to ensure that none are double counted. Secondly, the rate of decline (detectability decline) of calls with distance from the transect line must be known and used to limit or correct the number of calls counted to estimate density. Thirdly, the proportion of koalas within the sample population that call while observers are passing must be determined. The rate at which koala calls decline with distance suggests that all or most calls are detectible within 150 m, so counts to this distance can potentially be used for density estimation when faint or distant calls and those more than 150 m from the observer are excluded. In 1996, 1998 and 1999 a small percentage (average 4%) of all calls was considered likely to have been made by females because they were quieter, or involved screaming rather than bellowing, and were sometimes made in response to male bellowing. All calls were included in our decline analysis. Our data provide no direct information on the proportion of male koalas in the sample population that called during the period of about 10–20 minutes while observers were passing. However, it is possible to get a rough estimate of this portion by comparing the density of calling koalas with the expected density (calculated as half the density of koalas seen by spotlighting) assuming an even sex ratio across the sample population. This comparison revealed that the density of calling koalas was about two thirds of the level expected from direct sightings in 1996 if all males called and sex ratio was parity, and equal to or slightly higher than expected in 1998 and 1999.

Relationship Between Koalas Seen and Koalas Heard

We initially expected male koala call rates to be a constant multiple of koala sightings, and to test this hypothesis, we correlated the number of calls with the number of sightings on each transect after standardizing all calls and sightings to rates per kilometre to account for variations in transect length. In 1996 there was no apparent trend or significant linear correlation (r^2 0.02 – 0.04) between call rates and koala sightings/km (Figure 7). When data were analyzed separately for 1998 and 1999 there was a low (r^2 0.19, P <0.025) significant positive linear correlation between calls and sightings in 1999, and a low (r^2 0.11, P <0.05) near-significant negative linear correlation between calls and sightings in 1998. When call data were combined for the 1998/99 data these trends cancelled each other out and there was no significant correlation between calls and counts (Figure 8). The weak or lack of correlation between calls and counts, and especially the large number of calls on transects in low quality habitats, suggested that male and female koalas are distributed differently across the Pine Creek State Forest with calling males more abundant in low quality habitat and females more abundant in high quality habitat. To further explore this hypothesis, the difference between total numbers heard/km and numbers seen/km on each transect in 1998 and 1999 was regressed against mapped koala habitat quality (zones 0–5) after dividing the numbers heard by 6.3 to correct them to the same mean detection rate as sightings (an average of 0.39 koalas/km each year or 0.8 koalas/km for combined 1998/99 data). A significant (F 7, P 0.01) negative linear relationship described the difference between calls and sightings and increasing habitat quality (Figure 9). In low quality habitat (zones 1–2), 87% of transects had positive scores (calls exceed sightings) compared with 43% of sites with positive scores in high quality habitat (zones 4–5). In all three survey years moderate to high numbers of koalas were heard calling on transects where no koalas were sighted.

An anonymous reviewer suggested to the authors that the lack of correlation between sightings and calls could be accounted for by decreased visibility of koalas in low quality habitat. To test this possibility we compared (t-test) the mean recorded distance to all sightings in 1998 and 1999 on transects in low quality habitat (zones 1–3) (13.5 m) with the mean recorded distance to all koala sightings in high quality habitat (zones 4-5) (12.6 m) and found no significant difference. This indicates that scarcity of koala sightings in lower quality habitat cannot be accounted for by differences in forest structure and decreased visual detectability. We also regressed estimated distance to calls (excluding faint calls) against mapped habitat quality and found no significant linear association and a clear horizontal trend, indicating that call detectability is uniform across all habitat zones and that higher call frequency in low quality habitat cannot be accounted for by increased audibility of male calls in low quality habitat.

Koala Habitat Preferences

Linear regression revealed a significant (F 16, P <0.0003, r^2 0.30) increase in koala sightings/km averaged for 1998/99 with increasing mapped koala habitat quality (Figure 10). Koalas were scarce to absent on transects in low quality habitat (zones 1–2) and moderate to abundant on transects in high quality habitat. Logistic regression also yielded a highly significant (P 0.002) relationship between frequency of koala sightings on transects and habitat quality (Figure 11). A logistic regression for sightings of confirmed healthy adult females only (mostly females with dependent offspring) was much steeper than the relationship for all koalas, indicating that females preferred the highest habitat quality classes (3–5). Too few confirmed male sightings were available for analysing trends for sighted males only. A linear regression between frequency of occurrence of koalas sighted on transects in 1998/99 (combined) and habitat quality (where degraded habitat in zone 6 is ranked as zero) provided the least noisy and most statistically significant (P <0.001) relationship with habitat quality, explaining 97% of the variation in koala frequency of occurrence (Figure 12). No significant linear association was found between the frequency of occurrence of male koala calls and habitat quality (Figures 11, 12) and no significant

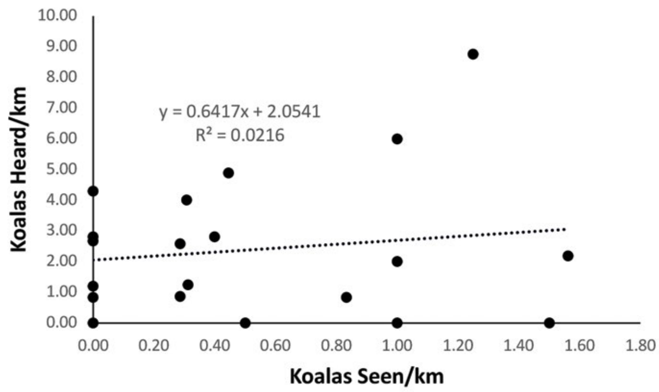

Figure 7. Correlation between number of koalas seen and heard on survey transects in 1996 showing the absence of a significant linear trend.

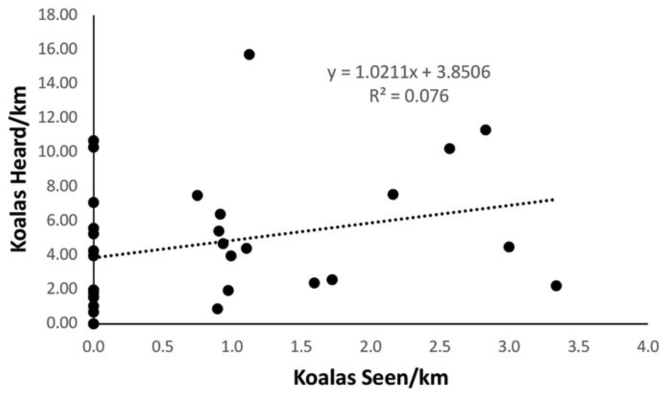

Figure 8. Correlation between number of koalas seen and heard on survey transects in 1998/99 showing the absence of a significant linear trend.

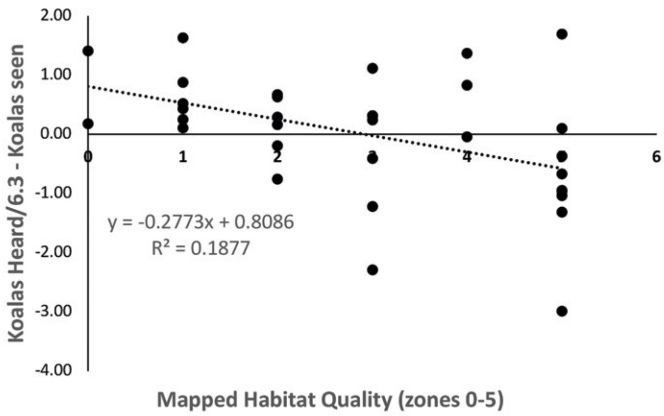

Figure 9. Difference between koala calls/km and koala sightings/km (after standardization to similar means) in 1998/99 data combined and regressed against mapped koala habitat quality, showing an overall decline in call rate relative to sightings with increasing habitat quality.

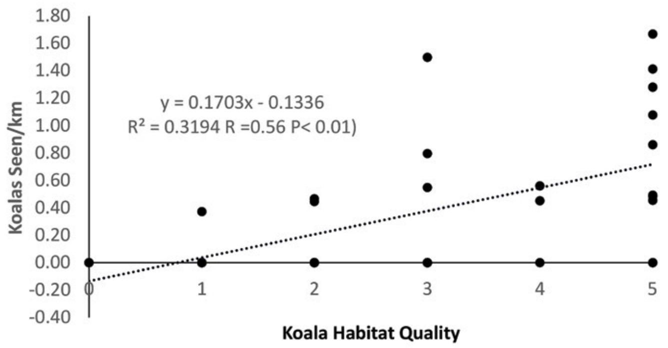

Figure 10. Linear association between koalas seen/km and mapped koala habitat quality (1–5) for combined 1998/99 surveys.

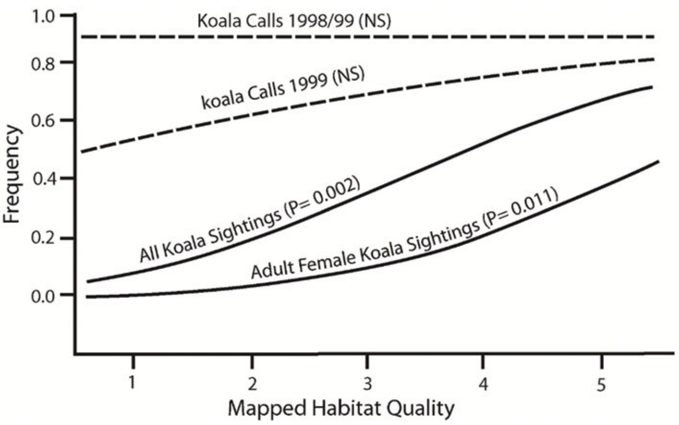

Figure 11. Results of logistic regression analysis of koala frequency of occurrence (0 - 1.0) on transects using calls 1999, calls 1998/99 combined, sightings of all koalas (1998/99 combined) and sightings of healthy adult females only (1998/99 combined). Broken lines indicate statistically non-significant relationships. Figure re-drawn by tracing over Statistica modelled output.

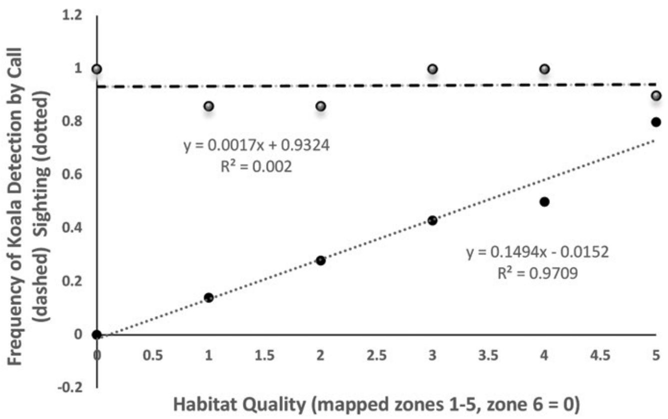

Figure 12. Best model of habitat quality showing the linear association between koala frequency of occurrence on transects and mapped habitat quality (0–5) for calls (dashed line) and sightings (dotted line) using combined data for 1998/99.

association was found between the number of calling koalas/km and habitat quality (Figure 13), indicating that male koalas were widely distributed across the landscape including areas unoccupied by females with young.

Koala Density and Population Trends

Koala sightings/km were converted to a measure of koala density (sightings/ha) by multiplying all animals seen out to 50 m either side of each transect by 2.6 (to account for animals present but not seen) and dividing by 10 (surveyed area 10 ha). Densities were averaged for each habitat zone and multiplied by the area of each zone in the Pine Creek State Forest in 1999 based on SFNSW (2000) mapping to obtain an estimate of population size. Results are presented in Table 3. Zone 6 was not included as this area was unmapped and included low as well as some medium and high-quality habitat. Koala density on the two transects surveyed in Zone 6 in this study was zero. Mean koala density was 0.018 koalas/ha or 56 hectares per koala in the lowest quality (Zone 1) cleared and planted native forest, about 2.5 times higher in even aged mostly planted Flooded Gum with some KFTS natural regrowth (zone 2) at 0.053 koalas/ha or 19 hectares per koala, about 5 times higher in medium to high habitat quality forest (zones 3 and 4) and 11 times higher in zone 5 at 0.2 koalas/ha., or 5 hectares per koala. Zone 5 forest was floristically and structurally similar to that in zone 4 but included areas with an abundance of previously reported koala records or sightings known locally as koala "hotspots". Overall density in zones 1–5 was 0.096/ha or 10.4 hectares per koala. The highest koala densities (0.28/ha) were recorded on a subset of five transects in parts of Pine Creek State Forest that were transferred to Bongil Bongil National Park in 2003 and which have been monitored annually since 2013 (see next section).

Table 3. Koala densities in habitat zones 1–5 based on koala sightings showing mean values for 1998/99 combined. Data for zone 6 (degraded or unclassified habitat) not calculated due to lack of adequate sampling.

Habitat Zone	Number of Transects	Koalas/ ha	Mapped Area*	Population
1	7	0.018	1972	35
2	7	0.053	844	45
3	7	0.098	706	69
4	3	0.083	261	22
5	10	0 203	950	193
Total	**36**	**0.076**	**3783**	**364**

*Areas from SFNSW 2000.

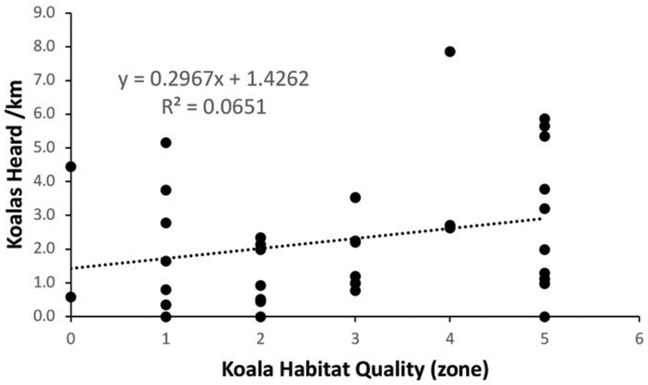

Figure 13. Correlation between koalas heard/km and mapped koala habitat quality (1–5) for combined 1998/99 surveys, showing the absence of a significant relationship.

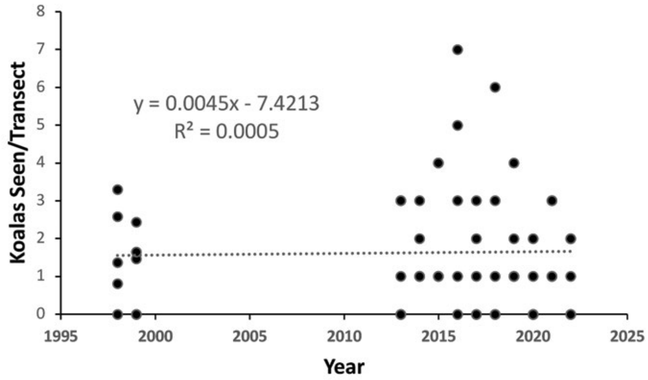

Figure 14. Koala population trends determined from sightings/1.5 km transect in 1998 and 1999 and 2013–2022 for five transects in high quality koala habitat.

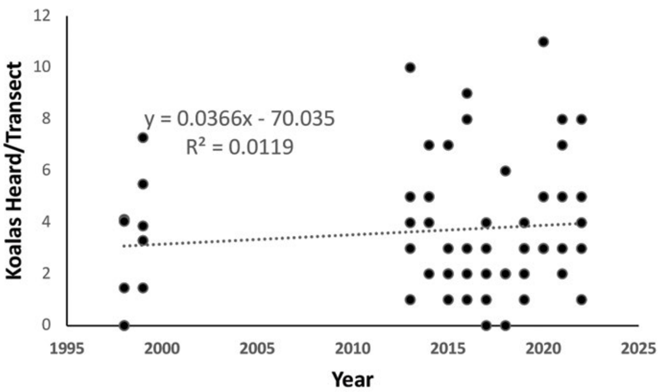

Figure 15. Koala population trends determined through male koala calls per transect in 1998 and 1999 and 2013–2022 for five transects in high quality koala habitat.

Total koala population size was estimated to be 364 individuals across 3783 hectares of mapped koala habitat. Total koala population size is likely to have changed since surveys were undertaken in 1999, increasing in unlogged habitats due to increases in tree size in zones 3–5, and recruitment of additional food tree species such as Tallowwood in zones 0–2, and decreasing in areas where subsequent clear-fell logging has been undertaken.

Long term annual monitoring of koala calls and sightings has been carried out since 2013 on or close to a subset of five of the transects surveyed in 1998/99 located in high habitat quality koala habitat (mapped zone 5) in Bongil Bongil National Park. State Forest at these sites was transferred to the park in 2003 where five 1.5 km-long transects have been monitored annually during the koala breeding season by volunteers (including the authors) since 2013. Survey methods were similar to those on transects in this study except that koala calls were played back at 500 m intervals followed by a short listening period. Average koala sightings/km on these transects in 1998/99 (0.91/km) were not statistically different (t-test) from averages recorded at the same (but slightly extended or adjoining) locations over the period 2013–2022 (1.12/km). Trend lines fitted to the monitoring data exhibit a high degree of variation from year to year but a near horizontal long-term trend (Figure 14). Average koala calls per/km in 1998/99 (2.07/km) were lower, but not significantly different, from the average during 2013-2022 (2.56/km). No significant relationship was found between the number of koalas seen and the number of koalas heard on individual monitoring transects from 2013–2022, consistent with the similar lack of correlation across all surveyed transects in the wider Pine Creek State Forest study area in 1998/99 (Figure 15).

DISCUSSION

The primary aims of this study were to: 1) test and validate the findings of earlier scat-based koala surveys in the study area which predicted that koalas prefer structurally complex forest with a high diversity and abundance of KFTS and no intensive logging history (Smith 1997, 2004; Smith and Andrews 2001); 2) test the accuracy of koala habitat mapping in the Koala Plan of Management; 3) test and validate koala density and population estimates across the study area and determine whether these are consistent (stable) over time based on analysis of long term monitoring data (1996–1998 and 2012–2022); and 4) provide a conceptual model of koala habitat that explains regionally unique variations in density, home range size, response to logging, dependence on forest structure and food tree choice. We confirmed that average koala density in natural forest in the study region is unusually low (0.1/ha or 10 hectares/koala in mapped habitat) relative to high densities (up to 13/hectare) reported for many reintroduced populations in natural and human-made habitats, especially in Victoria (Whisson and Ashman 2019). Koala density was not uniform throughout the forest but varied by a factor of 10 across a habitat quality gradient in which breeding females were largely limited to, or preferred, patches of forest with a high diversity and abundance of locally preferred tree species including non-eucalypts (*Allocasuarina* and *Syncarpia*), a complex more mature forest structure, and the absence of past intensive logging. Male and female koalas were distributed differently across the landscape with calling males more widespread and prevalent in low quality habitat, including plantation-like forests subject to past clear-felling and re-planting, where no breeding females were recorded. Koala density in the highest quality habitat (zone 5, 0.28/ha.) was relatively stable from 1998–99 and 2013–2022 at levels that can be expected to consume about 1-2% of annual leaf production.

There is no evidence of population irruption and food tree dieback characteristic of many high density reintroduced koala populations in southern Australia (Whisson and Ashman 2019). Exceptionally low koala density (0.018/ha) and the absence of females from plantation-like low quality habitat (zone 1) contrasts with reported high breeding koala densities (>0.8/ha) in Blue Gum (*Eucalyptus globulus*) plantations in Victoria (Ashman *et al.* 2020). These regional differences in koala habitat preferences and response to logging are not adequately explained by existing koala habitat models, especially those that rely on the occurrence of so called primary and secondary koala food trees, and those generated by examining associations between mapped environmental layers (e.g. climate, soils, forest type, recorded land use history) stored in Geographic Information System (GIS) and koala atlas records. To explain patterns of koala distribution and response to disturbance, we review the known habitat requirements of koalas and present a new hypothesis (in subsequent sections) based primarily on variations in foliage chemistry (toxicity and nutritional value) determined by the duration and stability of local plant-koala interactions in response to past fire, hunting, predation and logging disturbance history.

Koala Habitat

The study area was classified and mapped (by ground survey) on a 200 m grid into 5 zones of increasing koala habitat quality based on the occurrence of key, ground measured environmental site attributes previously found to be significantly correlated with koala scat abundance (Smith and Andrews 1997). These included the species richness and abundance of locally preferred koala food tree species (KFTS), forest age, forest structural complexity and the type and intensity of past logging in this landscape. Habitat quality zoning is effectively a gradient of increasing time since logging, decreasing logging intensity and increasing tree species diversity or naturalness. The highest quality habitat has only been lightly selectively logged to remove large and old senescent trees and is characterized by a high diversity of tree species and a high density of trees across all size classes, while the lowest quality habitat is characterized by young (20–35 year) structurally uniform trees often of a single species regenerating after clear-fell harvesting and replanting (Figure 3). The density and frequency of sighted koalas, especially adult breeding age females, broadly increased with increasing mapped koala habitat quality from 0.018/ha in low quality plantation-like forests to 0.2/ha in mapped high-quality habitat. Male koalas were more widespread across all habitats and moderately abundant in mapped low-quality habitat. This discrepancy could not be explained by reduced koala visibility or detectability in low quality habitat and is assumed to reflect real differences in male and female koala distribution.

The male koala population in the study area appears to comprise two parts, a resident breeding part that occupies higher quality habitat with breeding females, and a non-breeding or transient part that occupies low quality or unsuitable (sink) habitat with few or no breeding females. This pattern is consistent with the known social behaviour of male koalas, including their occupation of much larger home ranges than females, aggressive territorial exclusion of smaller or unsuccessful males, and female-biased sex ratios in some breeding areas (Eberhard 1978; Mitchell 1989; Ellis *et al.* 2001; Thompson 2006). It is also consistent with the results of radio-tracking studies by Radford Miller (2012), who captured and radio tracked 27 koalas in the study area and reported mean female home ranges of 6.4 hectares and males home ranges of 37 hectares. Female home ranges were mostly exclusive and rarely overlapped with other females, while male home ranges frequently overlapped other males and females. Females shared 53% of their (95% kernel) home ranges and males shared 34%, giving unique home range areas of about 4.8 hectares for females and 31 hectares for males or 13 hectares for both males and females if each koala uses half of each overlap zone and sex ratio is parity. Koala habitat was sexually segregated with males favouring areas with higher stem densities, smaller trees, and lower basal areas than females. Female home ranges also contained much greater proportions of preferred food trees Tallowwood and Grey Gum and lower proportions of Blackbutt and Flooded Gum than the male home ranges (Radford Miller 2012). A requirement for large unique home range areas is an unusual characteristic of the local koala population that requires explanation in habitat models and consideration in management.

Koala Habitat Mapping

A key aim of koala habitat modelling is to generate accurate maps of habitat quality for mapping koala distribution and estimating koala density and population size. Habitat maps can only be generated from models that predict koala abundance as a function of a limited number of "mapped" environmental variables stored in GIS layers. They cannot be generated using "unmapped" variables measured on the ground at survey sites such as forest age, forest structure, food tree diversity, the abundance of locally preferred food trees, or the occurrence of logged stumps and fire scars. This presents a significant limitation for accurate and reliable koala habitat mapping and population estimation in regional areas such as Pine Creek and Bongil Bongil National Park where koala density may vary more than 10-fold over short distances (200 m) in complex mosaics. To overcome this problem and develop a map that could more accurately predict koala density in non-plantation habitat, every 200 m grid square in the Pine Creek State Forest was subsequently surveyed, classified, and ranked on a gradient of 1–5 (SFNSW 2000). The reliability of this mapping was independently tested by Radford Miller (2012) and found to reflect a gradient of increasing KFT species richness, KFT basal area, tree species richness and tree stem density, while tree basal area was lowest in zone 1 and plateaued in zones 2–5. Koala habitat maps of the study area generated from predictive models that associate koala survey records with mapped environmental variables, such as topography, vegetation type, geology, soil type, modelled climate, and disturbance history (Law *et al.* 2015, 2017) may be statistically significant (when tested against subsets of koala atlas records used to generate the models) but generally lack the high level of accuracy and rigour essential for conservation management at local scales. Application of regional scale GIS models to local scale management has been shown to have serious adverse consequences for arboreal mammal conservation in Victorian timber production forests. Statewide models of Greater Glider distribution (Lumsden *et al.* 2013; VicForests 2019; DELWP 2020) used by VicForests as a planning and management tool to predict Greater Glider probability of occurrence in logging coupes (as a substitute for undertaking local ground surveys) failed to correctly predict Greater Glider occurrence in 46 out of 58 logging coupes (Smith 2021). A common cause of this inaccuracy is that the scale of predictions cannot, by definition, be any more spatially accurate than the scale of variation in the underlying mapped data used to make the prediction, and mapped data are often very coarse (kilometres to tens of kilometres), especially in the case of climate data which are extrapolated from a small number of climate stations. Law *et al.* (2017) claim to have generated a koala habitat model at a scale of 250 m resolution that could be used to guide management, but simply dividing coarsely mapped environmental variables into small squares does not improve their predictive accuracy or reliability to the scale of division.

Limitations of GIS modelling for koala habitat mapping in NSW were tested in 2015 by the NSW Environment Protection Authority. The predictions of five different koala habitat models generated using mapped environmental variables were tested against actual koala scat occurrence at a range of test sites in northern NSW (Smith 2015; EPA 2016). These models included: 1) a PCT (plant community type) model based on the likely occurrence of koala food trees in different mapped vegetation communities; 2) a RN17 forest type model that equated mapped forest types of Baur (1965) with primary, secondary on non-habitat; 3) an Office of Environment and Heritage (KHM) Boosted Regression Tree model that correlated over 10,000 known koala presence and absence sites with over 140 mapped or remotely sensed environmental variables; 4) a DPI Department of Primary Industries (Law *et al.* 2015) internally validated koala habitat model that predicts koala probability of occurrence in 250 m grid squares based on algorithms that compare koala Atlas records with a range of mapped environmental and landscape variables, and 5) an Office of Environment and Heritage baseline koala map (Predavec *et al.* 2015) which predicted the likelihood of koala occurrence based on the proportion of koala records from within a suite of mammal records in 10 km × 10 km cells. No significant correlation was found between the PCT, RN17, KHM models and koala scat abundance, and a significant negative correlation was found between scat abundance and the DPI (Law *et al.* 2015) model (Smith 2015). A significant, but poor, correlation (r 0.210) was found with the baseline koala map (Predavec *et al.* 2015) which demonstrates that koalas are more likely to be found in regions where they have previously been reported. Law *et al.* (2017) subsequently generated a 250 m resolution MaxEnt koala habitat model for northern NSW and south-east Queensland which they validated using independent acoustic surveys and a food tree model at 63 sample sites spread over geographic distance of around 500 km with a bias toward upper (28 sites) and lower slopes (32 sites) and state forests subject to timber harvesting. A significant correlation was found by Law *et al.* (2017) between predicted and actual male koala occurrence across the broad survey region, but the relevance of this model to female koalas is uncertain, and much of this habitat could be unsuitable or simply represent sink habitat occupied by transient, roaming male koalas. Because the model was generated over a large geographical distance, the resulting statistical associations with male koala occurrence could have been driven largely by broad (regional scale) differences in primary productivity (eucalyptus leaf biomass) that change predictably with elevation and climate.

Koala Population Stability

Koala populations have the capacity to expand rapidly and attain abnormally high densities (1-18/ha) in some offshore islands, mainland remnants, peri-urban habitats and plantations where they have been introduced or re-introduced after long periods of prior absence. These unnaturally high densities commonly lead to dieback and death of preferred food trees and subsequent koala population declines (Masters *et al.* 2002; Whisson and Shimmin 2006; Wallis 2013; Whisson *et al.* 2016; Menkhorst *et al.* 2019; Whisson and Ashman 2020). Koala population irruptions in areas where they have been introduced after a long period (thousands of years) of scarcity or absence provides strong evidence that koala food trees lose their resistance to koala browsing after periods of koala absence, and therefore that over the long term browsing pressure by koalas regulates the tree species composition of natural forests by selectively eliminating less well-defended tree species and individuals over time. It follows from this argument that koala density should be lower in natural forests with stable populations and a long stable history of browsing pressure. Low koala density in the Pine Creek State Forest and Bongil Bongil National Park study area is consistent with this model. The area supports a mosaic of tall wet and dry sclerophyll forest and rainforest on undulating topography across a network of moist drainage lines which provides a high level of protection against intense fire and drought, enabling this region to support one of the largest and most stable koala populations in NSW (Smith 1997). Koala population density (0.28 animals/hectare) in high quality habitat (zone 5) in Bongil Bongil National Park within the study area has been relatively stable for most of the past 25 years despite significant climate fluctuation and drought during this period (Figure 14). Stable koala densities have also been reported in similar forest habitat in the Richmond Range region of the NSW north coast (Goldingay *et al.* 2022) and within the broader Coffs Harbour region, despite the occurrence of drought (Lunney *et al.* 2015). This relative stability of koala density in mid-low elevation north coast forests is strong evidence that koala populations in these forests are at carrying capacity and 'in balance' with their host trees.

Female koalas are unlikely to occupy home ranges larger than necessary to satisfy their energy and nutritional requirements for growth and reproduction because this will increase predation risk and increase unnecessary energy expenditure. Free living koalas consume about 70 kg (males) to 85 kg (lactating females) of dry leaf per year (Nagy and Martin 1985; Krockenberger 1993) or up to 25 kg/hectare per year at densities of 0.29 koalas/hectare. This is around 1% of expected annual leaf production in a high rainfall forest with an annual litter fall of 5000 kg/hectare/year (of which about half is assumed to be edible leaf and the balance bud, stem and bark material, Grigg and Mulligan 1999). Greater Gliders, which also feed almost exclusively on *Eucalyptus* foliage, have a similar impact on *Eucalyptus* foliage, consuming about 18 kg leaf per year (Foley *et al.* 1990) or 18 kg dry leaf per hectare per year at densities of 1/hectare. Greater Gliders are 5-6 times smaller than koalas but occur at higher densities (0.5-2.0/ha) and feed more selectively on young growing tips of larger trees rather than mature adult leaves (Henry 1985). Greater Gliders are present in the study area but occur at lower densities than koalas due to a scarcity of old growth trees with hollows (Smith and Andrews 1997). Relatively low levels of leaf consumption by these arboreal folivores indicate that *Eucalyptus* trees in natural forests have evolved successful defensive mechanisms for limiting mammalian herbivore browsing rates to around 1-2% of total annual leaf production on average across the landscape, or up to 5% of leaf production in some preferred tree species. Levels of 1-2% loss are small relative to average annual leaf area loss in *Eucalyptus* forests (5-15%, Gherlenda *et al.* 2016) from all sources including insects, and are unlikely to adversely impact the growth and survival of host trees. Higher levels of folivore browsing, such as those in introduced high density koala populations on offshore islands in Victoria associated with tree dieback are, however, highly likely to result in long-term selective elimination of susceptible trees and increased survival of individual trees with a greater capacity for induced or inherent koala defense.

Stable populations are those in which either reproductive and recruitment rates equal rates of mortality and territory abandonment, or in which those individuals surplus to population capacity (unable to find suitable unoccupied habitat) are forced to disperse into unsuitable sink habitats where they are unlikely to survive and reproduce. Both strategies occur in koala populations. Martin (1985) reported a decline in koala fertility following defoliation of preferred food trees in Victoria, and Eberhard (1978) found that a koala population on Kangaroo Island was regulated by increased mortality amongst dispersing sub-adult koalas. The results of our surveys, in conjunction with radio-tracking studies in the same area (AMBS 2011; Radford Miller 2012), are consistent with a population regulation strategy in which surplus male koalas are forced to disperse into low quality habitat where they fail to reproduce, and female koalas establish home ranges in high quality habitat and reproduce in years when sufficient food of suitable quality is available to provide them with the additional nutritional and energy requirements for lactation. Lactating female koalas require up to 20% more food intake than non-lactating females (Krockenberger 1993). Vegetation in the study area is a mosaic of forest patches of different habitat quality (Figure 2) including some patches that are smaller than an average koala home range. Radio-tracking studies of the koala throughout the Pine Creek State Forest between 1999 and 2002 (Radford Miller 2012) have shown how koalas utilize this mosaic. Forty percent of female home ranges and 73% of male home ranges included multiple mapped habitat quality zones. Koalas were selective in their location of home ranges, but once settled koalas used all *Eucalyptus* tree species within their home range in approximate proportion to availability, except for patches containing Grey Gum that were occupied more than expected. Koala home ranges were located non-randomly with respect to forest type, with habitat zones 3–5 preferred followed by zone 2, then zone 1 and last zone 6. Vegetation within koala home ranges contained a higher density of *Eucalyptus*, and higher richness of KFTS, more KFTS, and almost twice as many Tallowwoods and three times as many Grey Gums and Iron Barks as random vegetation samples. Koala habitat was sexually segregated with males favouring areas with higher stem densities, smaller trees, and lower basal areas than females. Female home ranges also contained much greater proportions of preferred food trees Tallowwood and Grey Gum and lower proportions of Blackbutt and Flooded Gum than the male home ranges (Radford Miller 2012). Despite the importance of KFTS in selection of home ranges there is no evidence that preferred food trees within home ranges are excessively targeted or defoliated; instead, radio tracking showed that browsing koalas change food trees regularly and frequently, seldom feeding on the same individual tree twice.

Koala Food Trees

In theory, koala density should be broadly limited over the long term by a combination of primary productivity (the amount of leaf produced per hectare of forest) and the proportion of leaf that is palatable to koalas. Koalas are well known to be fussy eaters and to prefer a limited number of *Eucalyptus* species, commonly referred to as 'Primary' or 'Secondary' koala food trees (DECC 2008). Classification and mapping of vegetation communities according to their proportion of primary and secondary koala food trees based on listings such as those in the NSW Government Recovery Plan for the koala 2008 (now superseded) is a common approach to modelling koala habitat for conservation and management purposes (Mitchell *et al.* 2021), and has been used to 'pseudo-validate' koala habitat models (Law *et al.* 2017), even though there is no proven correlation between koala density and mapped forest type at local scales (Smith 2004, 2015). Smith and Andrews (1997) tested the accuracy of SFNSW forest type mapping in the Pine Creek State Forest by ground survey at 119 sites and found that only 35% (range 0–70%) of sites were correctly mapped.

Koala dietary preferences vary considerably between localities and regions (OEH 2018), and frequently include tree species not listed as primary or secondary koala food trees in policy and planning documents (Ellis *et al.* 2002b; Sullivan *et al.* 2003; Smith 2004; Woodward *et al.* 2008; Cristescu *et al.* 2011). The second most frequently consumed koala food tree species in the Pine Creek State Forest (*A. torulosa*) is not included on the DECC (2008) koala recovery plan list of koala food trees for the NSW north coast. An analysis of koala scats from the Pine Creek State Forest (Smith 2004; MacGregor K. unpublished) found koalas to feed on almost all the available *Eucalyptus* and many non-eucalypt tree species (16+ species) in the study area, but to prefer some tree species more than expected and others less than expected based on their natural occurrence (Figure 16). The most abundant remains in scats were from Tallowwood (39%), Forest Oak (11%) Sydney Blue Gum (9%), Grey Gum (7%) and Turpentine (6%). Sydney Blue Gum was consumed about four times more than expected, Tallowwood 2.6 times more than expected, Grey Gum 2 times more than expected, Turpentine 2.5 times less than expected and Forest Oak 1.5 times less than expected on the basis of tree occurrence in survey plots where scats were collected. Blackbutt, which is a common dominant tree in Pine Creek State Forest, was consumed 4 times less than expected, but is a favoured food tree on Stradbroke Island, while Brush Box (a non-eucalypt) contributed only 1% of the diet in the Pine Creek State Forest but was the equal most frequent species in koala scats on Stradbroke Island (Cristescu *et al.* 2011). Eucalypts in the genus *Corymbia* were largely avoided in the Pine Creek State Forest but have been reported in moderate abundance in the diet of koalas in the Sydney region (Sluiter *et al.* 2001). Red Gum, which is a well-known primary koala food tree, was eaten less than Blackbutt on North Stradbroke Island and little more than Brush Box (Woodward *et al.* 2008).

Exploitation of *Syncarpia* and *Allocasuarina* appears to be locally unique in Pine Creek State Forest and Bongil Bongil National Park. The potential importance of these and other non-eucalypts has not been evaluated in dietary studies supported by the NSW Natural Resources Commission (NRC 2022). Feeding on Forest Oak may be important to koalas at this locality because of its nitrogen fixing capability and likely high foliage nitrogen content. Radford Miller (2012) found that female koalas increase their intake of *Allocasuarina* during the breeding season and decrease their intake of Grey Gum and Blue Gum. Supplementing the diet with Forest Oak should enable koalas to increase their protein intake for reproduction and exploit more eucalypt foliage with low available nitrogen levels, including older mature leaves and the foliage of eucalypt species in the subgroup *Monocalyptus* (now *Eucalyptus*) which typically have high nitrogen binding tannin levels that reduce protein intake below levels required for maintenance. Radford Miller (2012) also found that intake of *Monocalyptus* (Blackbutt and White Mahogany) increased during the koala breeding season in Pine Creek State Forest. Smith and Andrews (1997) found that *Allocasuarina* was scarce (10% of levels in all other forest types) in previously clear-felled and replanted forests, indicating that this species is likely to be particularly sensitive to elimination or reduction under current intensive logging practices.

Local and regional variations in koala food tree preferences have been attributed to four main known causes; a) inherent (genetic) variations in palatability and toxicity between tree species and individuals, b) environmental site variations in toxicity between individuals within the same tree species inhabiting different regions (Moore *et al.* 2004), c) induced changes in levels of leaf toxicity and palatability in response to folivore browsing pressure (Borzak *et al.* 2017), and d) differences in individual koala gut microbiomes, which affect their ability to detoxify or overcome the chemical defenses of different tree species (Marsh *et al.* 2021). *Eucalyptus* trees have at their disposal a wide range of chemical defenses for reducing herbivore browsing including water content, fibre and lignin content, protein content, protein binding tannin content, toxins (particularly oils), and antifeedants that suppress intake including formylated phloroglucinol compounds (FPCs) and unsubstituted B-ring flavanones (UBFs) (Ellis *et al.* 1995; Moore and Foley 2000, 2005; DeGabriel *et al.* 2009; Marsh *et al.* 2019). Considerable variation has been reported in the levels of these chemicals between tree species, between individuals within species and between leaves within trees (especially between young and old leaves and leaves in the upper vs lower crown). Habitat models for eucalyptus folivores that rely on forest type or community type or rely on lists of so-called primary koala food trees, for mapping and impact assessment (e.g. Law *et al.* 2017; NRC 2022) seldom account for this considerable intraspecific variation in foliage quality. Moore *et al.* (2004) found that levels of phenols, FPCs and oils in Tallowwood, the most preferred food tree of the koala in the Pine Creek State Forest, varied more than 4-fold between individual trees, increasing linearly with site quality, elevation and decreasing with mean minimum atmospheric temperature. High levels of variation between individual trees in different regions provides an environment for selective elimination of less well-defended trees in habitats with high levels of folivore browsing pressure. Moore *et al.* (2004) found that koala scats were more common under larger, less chemically defended individual trees with lower levels of cineole and the koala antifeedant FPC sideroxylonol. Excessive targeting of such individual trees by koalas over time can be expected to lead to a reduction in their growth and competitiveness and their eventual displacement by more heavily defended individuals, except where these trees are able to induce higher levels of defense in response to folivory.

Most studies of associations between koala food tree preferences and leaf toxicity and nutrient levels have been based on analysis of single leaf samples and an assumption that leaf chemistry is fixed or constant over time (age) and space (within the canopy) within individual trees, but there is little evidence to justify this assumption and significant evidence to the contrary. Eucalyptus trees shed their leaves every 2–4 years and generally reduce the levels of nutrients in leaves as they

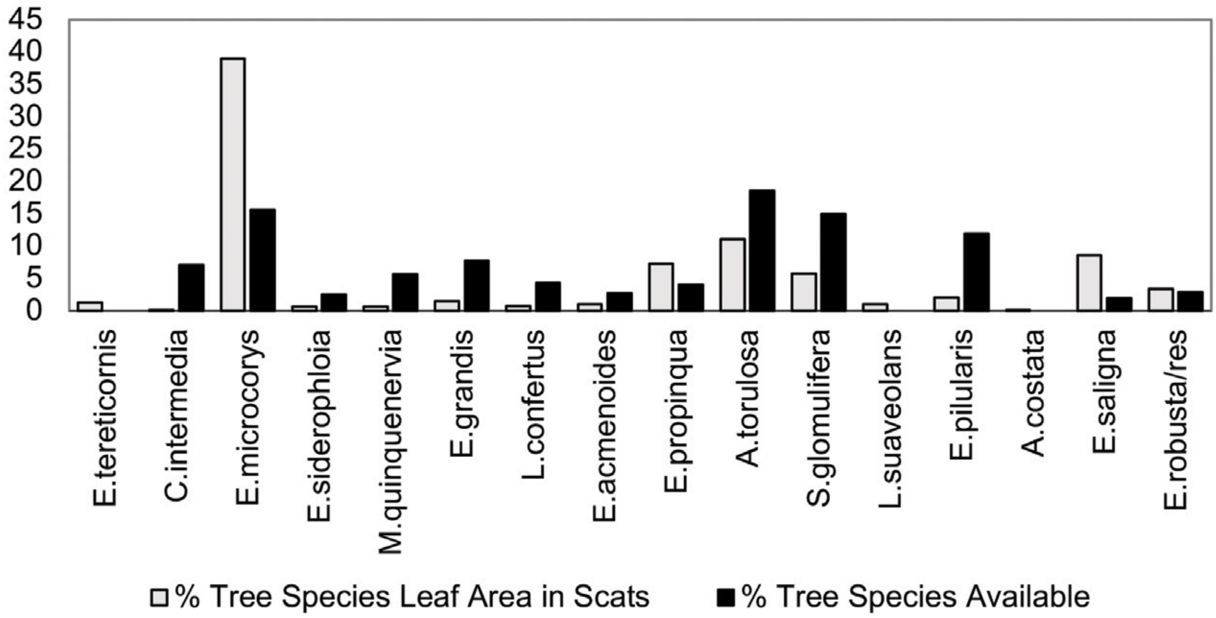

Figure 16. Percentage area of remains from different tree species in koala scats in the Pine Creek State Forest relative to tree species abundance in scat survey plots showing koala diet preferences (after Smith 2004 and MacGregor 1997 and unpublished).

age, re-directing them to new growing foliage before they are shed (Fife *et al.* 2008). This indicates that eucalypts have the capacity to move chemicals around the canopy and potentially to increase the level of toxins and antifeedants in direct response to herbivore browsing (induced toxicity). Plants are known to increase airborne volatile signals to neighbouring branches and to send down stem signals via the plant vascular system in response to leaf wounding (Heil and Ton 2008). When koalas chew on *Eucalyptus* leaves they release volatile compounds with the potential to alert neighbouring branches and trees of the attack, allowing the tree to mount an induced defense by raising levels of toxic chemicals and antifeedants in new or existing leaf growth.

Studies of toxins in seedling *E. globulus* trees (Borzak *et al.* 2017) have shown that levels of sideroxylonal and cineole are 30–50% higher in new than old leaves, and that levels in new leaves are further elevated by 24–37% in trees that were partially defoliated relative to control trees that were not defoliated. The increase in toxin levels in new leaves regenerating after defoliation was accompanied by a comparable decrease in toxin levels in older retained leaves lower in the canopy, indicating that this change is an induced response by the tree to increase protection of new leaves which are those most frequently targeted by insects and mammalian herbivores, particularly smaller folivores such as greater gliders (*Petauroides volans*) (Henry 1985; Kavanagh and Lambert 1990). Condensed tannins, which are thought to inhibit browsing by mature leaf-eating mammalian folivores like koalas by binding with proteins and reducing digestible nitrogen intake below maintenance levels (DeGabriel *et al.* 2008), also varied with leaf age and defoliation history but in a reverse direction. Condensed tannins were 50% more abundant in older leaves in the lower crown and increased by a further 30% in older, lower leaves of trees that were partially defoliated. These findings show that individual *E. globulus* seedlings can respond to defoliation by increasing the cineole and sideroxylonal content of new young leaves (by transfer from older leaves) and by increasing the condensed tannin content of old or mature leaves. The magnitude of these induced changes equalled or exceeded natural underlying genetic differences in toxin levels between individual trees sampled from different geographic regions.

These findings, which show that koala food trees are not passive participants in forest ecosystems but can actively elevate their chemical defenses in response to browsing, have profound implications for koala conservation and management. They bring into question the results of previous studies of associations between koala density and foliage chemistry which have relied on single leaf samples and an assumption that leaf chemistry is constant (genetically fixed) rather than varying with recent folivore browsing history on the sample tree, sample branch, or potentially also on neighbouring trees. They also predict that arboreal folivores should limit browsing of individual trees to low levels that do not trigger an induced increase in toxicity in new leaf growth by changing food trees frequently and by not returning to a browsed tree for long periods or until after induced increases in toxicity have returned to background levels. Observations of feeding by arboreal folivores confirm that this is how they typically behave. Greater gliders change individual food trees frequently, harvest only a small portion of foliage on each tree during each feeding bout and move daily despite the increased exposure to predators (Henry 1985). Koalas similarly change food trees frequently, move about 180 m daily despite the increased risk of predation when coming to the ground to move between trees, seldom feed on the same tree twice within long observation periods, and progressively feed on almost all the available *Eucalyptus* tree species and individuals and many non-eucalypt trees within their home ranges (Krockenberger 1993; Matthews *et al.* 2007; Ellis *et al.* 2009; Matthews *et al.* 2016; Radford Miller 2012). In Pine Creek State Forest, Radford Miller (2012) observed koalas in trees where a koala had previously been sighted on only 78 out 711 occasions (11%) during radio tracking surveys of up to 6 months duration. Scat analysis of koala diet in Pine Creek State Forest (Smith 2004; MacGregor K. unpublished) found an average of 10 different tree species per scat and remains of almost all the available *Eucalyptus* and many non-eucalypt tree species (16+ species) across the study area.

The need to minimize induced toxicity in host trees by changing food trees after feeding and not returning for long periods would explain why koalas require such large home ranges and have relatively low densities in natural forests with long history of browsing pressure, such as those in the study area. Induced toxicity, particularly in new leaf growth, provides a simple, plausible feedback mechanism for host trees to regulate koala browsing pressure in forests to levels that do not adversely affect tree growth and survival. That this feedback mechanism has failed in areas where koalas have been reintroduced resulting in population irruptions and tree dieback, does not negate its existence or importance in areas of natural forest with a long history of koala browsing. It simply highlights the need for eucalypts in areas where koalas occur to have either high inherent (genetic) levels of toxicity or a high capacity to increase toxicity in response to browsing, or both.

Recent evidence indicates that the ability of koalas to exploit different tree species in different regions and seasons is related to localized variations in the occurrence of specialized microorganisms in their gut microbiomes (Marsh *et al.* 2021). Individual koalas have site specific gut microbiomes which they inherit from their mothers or other females by ingestion of special maternal faeces, or 'pap', excreted directly from the caecum. Pap inoculates young with microflora enabling them to digest *Eucalyptus* and other leaves after weaning. Pap has a high water content (82%) and 23–41 times higher count of tannin-protein-complex degrading enterobacteria than normal faeces (Osawa *et al.* 1993). Gut microbiomes differ between individual koalas and these differences limit the tree species that individual koalas ingest. Certain streptococci and enterobacteria found in koalas that feed on eucalypts in the subgroup *Monocalyptus* (characterized by high levels of tannins and low levels of available nitrogen) may be essential for releasing tannin-bound proteins and making this tree group more palatable (Osawa 1992; Osawa *et al.* 1993). Similarly, Ruminococcaceae found in koalas feeding on Messmate (*Eucalyptus obliqua*) are thought to assist koalas in the digestion of recalcitrant celluloses, enabling them to maintain energy balance on the tough, highly fibrous foliage characteristic of this species (Brice *et al.* 2019; Marsh *et al.* 2021). Once these essential taxa have been lost from koala microbiomes, which is likely to occur in individuals that feed on a few easily digestible species, or single tree species, in captivity, plantations or logging regrowth, there is no evidence that they can be regained in the short term.

Koalas brought into captivity and fed different tree species are unable to change their microbiome unless they are inoculated with gut microbes from other individuals adapted to different diets (Blyton *et al.* 2019). This suggests that koalas can only eat leaves from some trees species if they have an appropriate microbiota, and that composition of the gut microbiome is likely to influence and limit koala food choice. The microbiome of translocated koalas has been found to influence the species of *Eucalyptus* they ate in their new habitats (Blyton *et al.* 2023), suggesting that koalas must select tree species compatible with their gut microbiomes. A low diversity or absence of suitable gut microbiomes could explain why some dispersing and translocated koalas move large distances (Close *et al.* 2017) and why koalas are frequently absent from large areas of apparently suitable habitat. It may also explain the existence of koala "hotspots", and why one of the best predictors of koala occurrence is where folivores have been recorded before (Predavec *et al.* 2015; this study). Selection and development of locally specialized gut microbiomes may explain why koala populations in the study area are able to exploit locally unique food trees, like *Allocasuarina* and *Syncarpia*, and why koalas appear to utilize and adapt to feed on most of the locally available *Eucalyptus* (and some other) species over time. If this hypothesis is correct, the elimination of koala populations from large areas after intensive/extensive disturbances such as wildfire, intensive logging and drought may disrupt the continuous transfer of locally adapted gut microbiomes from mothers to daughters and prevent population recovery.

Limitations of Call Monitoring

The absence, or low density, of breeding female koalas in young (20–30 year old) uniform-aged forest dominated by a low diversity of tree species reported from scat surveys by Smith and Andrews (1997), and confirmed in this study, is evidence that forest regenerating after high intensity, clear-fell logging of the type carried out in the Pine Creek State Forest since 2005 (Figure 3) and currently underway in nearby forests (J. Pile, A. Smith unpublished observations) is unlikely to support breeding female koalas. This conclusion is irreconcilable with recent claims by the NSW National Resources Commission (NRC 2021, 2022) that "*intensive harvesting occurring in the past five to 10 years is unlikely to have impacted koala density*" and findings of Law *et al.* (2022b) that "*native forestry regulations provided sufficient habitat for koalas to maintain their density, both immediately after selective harvesting and 5–10 years after heavy harvesting*", based on use of remote call recorders to model male koala distribution and response to harvesting in NSW timber production forests and reliance on an unproven assumption that male and breeding female koala distribution and habitat preferences are identical. The findings of this study demonstrate that this assumption is invalid in Pine Creek State Forest.

The frequency of koala calls in the Pine Creek State Forest did not correlate with the combined number of male and female koalas sighted, and the distribution of male koala calls differed from that of female koala sightings. These findings confirm that male and female koalas are distributed differently across the landscape, with calling males widespread in both low and high quality habitat while adult breeding females are largely confined to high quality habitat, consistent with the earlier findings of independent radio tracking studies by Radford Miller (2012). It is also consistent with conclusions from dietary studies on St Bees Island in North Queensland (Tucker *et al.* 2007) that young koalas may be excluded from preferred tree species while dispersing, and the reported social behaviour of koalas generally, in which population regulation is achieved by territorial exclusion and dispersal of surplus young, especially males (Eberhard 1978; Gordon *et al.* 1990).

Our findings lead us to conclude that the failure of Law *et al.* (2022b) to find an impact of intensive logging on koalas is most likely an example of a type-2 statistical error (acceptance of a null hypothesis that there is no effect of timber harvesting when in fact there is) caused by widespread distribution of transient male koalas in suboptimal or sink habitat, and deficiencies in habitat modelling that rely on limited available mapped GIS layers (Smith *et al.*

2002; Law *et al.* 2017; NRC 2020, 2022; Goldingay 2022) rather than ground surveys of unmapped variables for prediction. We conclude from these findings that koala habitat models, especially those based on acoustic monitoring and large-scale GIS layers, are not reliable replacements for actual ground survey of koala habitat characteristics and female koalas for making important decisions about koala conservation and management.

Law *et al.* (2018) proposed that acoustic surveys of male calls can account for imperfect detection of koala presence by other methods (scat surveys, spotlighting) for the purpose of koala conservation and management because large numbers of recorders can be deployed at low cost and detection frequency per site is higher than for other survey methods. While it is true that call recording is more cost effective and efficient that direct observation, the results of our study show that acoustic surveys are unreliable for detecting and defining core koala breeding habitat and are therefore unsuitable for core koala habitat modelling, mapping and impact assessment. Core koala habitat has been defined as "*an area of land with a resident population of koalas, evidenced by attributes such as breeding females (that is, females with young) and recent sightings of and historical records of a population*" (NSW Government State Environmental Planning Policy NO 44 SEPP 44). This is an important definition because it recognizes that the most important koala habitat for conservation is that part of the landscape in which female koalas successfully reproduce over the long term. The frequency of koala calls in the Pine Creek State Forest did not correlate with either the total number of koalas sighted (male and female) or with the number of confirmed female koala sightings. This result was not unexpected as male koalas have higher levels of mobility, larger home ranges and lower energy and nutritional requirements than similar sized females.

In addition to its failure to distinguish between male and breeding female habitat, call recording may have other limitations. Call rates vary strongly with season, weather, and time of day (Ellis *et al.* 2011; Hagens *et al.* 2018) and calls may be difficult to identify with certainty on recorders when scanned with acoustic software without time consuming manual checking for false positives and negatives (Law *et al.* 2017). Not all male koalas may call, male response to other male calls may vary with the social status of the caller and listener. In southeast Queensland adult males typically approach the calls of other males, especially small ones, while juvenile males ignore or move away from calls and females show no response (Jiang *et al.* 2022). Koala calls are recorded over such large areas (about 25 hectares) that there is a real chance of recording false presences because koalas are calling from a patch of different habitat type from that surrounding the recording locality. The number of koala calls per site made by remote recorders cannot be used as a quantitative measure of koala call abundance because it is not possible to distinguish between multiple calls made by one individual and single calls made by multiple individuals. This problem is usually overcome by measuring the frequency of sites where koalas are present as a measure of koala abundance. However, the relationship between animal frequency of occurrence and animal density is non-linear (Caughley 1997) except at low frequencies (<20%). At high frequencies (>70%), density may increase 5-fold with only small changes in frequency (within bounds of chance or normal random variation), which means that the chance of making a type-2 error greatly increases, and significant associations with environmental variables may be missed or disguised by normal background noise. This often occurs with acoustic monitoring because of the large areas surveyed (>25 hectares) and the long time period that recorders are left out (7 days or more).

It has also been shown (Hagens *et al.* 2018) that the probability of recording koala presence using acoustic recorders increases with the number of survey nights in low quality habitats from near zero after one night to 100% after ten nights. In this study we found male call frequencies to exceed 80% in combined 1998/99 survey data after just 20–40 minutes of listening, which was too high for reliable analysis of frequency associations with mapped habitat quality (Figure 11). Law *et al.* (2022) reported very high detection frequencies across survey sites of 89–100% before and after timber harvesting. Reliance on remote recorders (song meters), or unsighted calling koalas, also precludes any opportunity to gather additional important information about koala health, sex, age, and reproductive status and consequently fails to distinguish between core breeding habitat (where the population is stable or expanding) and sink habitat where the population is constantly renewed by immigration of a dispersing surplus from elsewhere. One study (Hagens *et al.* 2018) has reported a significant correlation between male koala calls/h on acoustic recorders and koala density at 10 survey sites across the state of Victoria, which is inconsistent with our findings. However, this result could be driven by an overly steep koala density gradient (akin to fitting a linear regression between two points or two clusters) arising from inclusion of unnaturally high-density koala populations (3–8 animals/ha) in a plantation at Bessiebelle (southwest Victoria) and introduced populations at Cape Otway and Phillip Island (southern Victoria) in the database. When this correlation is re-run in Excel (using the published data) with just the 7 more normal density populations (<2/ha) there is no significant correlation between koala density and male koala calls/h, consistent with findings in this study.

Koala Response to Logging

Breeding females koalas were more abundant in older more structurally complex forests, consistent with findings of numerous other studies that koalas prefer larger trees for both sleeping and feeding (e.g. Lunney *et al.* 2000; Moore and Foley 2000; Phillips and Callaghan 2000; Matthews *et al.* 2007; Ellis *et al.* 2009). Hindell and Lee (1987) found koalas in the Brisbane Ranges of Victoria to prefer larger trees and forests with a higher density of medium to large trees. Marsh *et al.* (2013) found that koalas spend more time resting in larger trees because they provide suitable forks for sleeping but spend time in smaller trees at night. In drier parts of their range at Gunnedah on the northwestern slopes of NSW koalas have been found to select larger and taller trees during the day to provide shelter from heat in summer (Crowther *et al.* 2014). A 10-year study of tree selection by koalas on Phillip Island found them to prefer trees of larger size but to select individual large trees with lower levels of FPCs and higher levels of nitrogen (Moore and Foley 2005). In Pine Creek State Forest, Smith and Andrews (1997) found that koala scats were more abundant than expected at the base of larger trees and there was a general increase in scat abundance with increasing forest age, structural complexity, and predominance of larger stems. Scats occurred more frequently than expected in trees of 30–120 cm diameter at breast height (dbh) and less than expected in trees under 20 cm dbh. Koala scats were found under 10–20 cm diameter trees but only in stands with a mixture of larger trees including some >50 cm dbh. Koala scats were absent from uniform-aged regrowth (plantation) stands less than about 35 years of age and with no stems >50 cm dbh. Scats were most abundant in mixed age forests with a high overall tree stocking (tree density) in all size classes including young regrowth (10–40 cm dbh), advanced regrowth (41–60 cm dbh) and mature (60–80 cm dbh). There was a general linear increase in scat density with the number of tree stems >50 cm dbh per hectare. Radio tracking studies in the Pine Creek State Forest have shown that these structural preferences differ between the sexes, with males more prevalent in uniform young stands and females in structurally complex older stands (Radford Miller 2012). These earlier findings are corroborated by the present study which found male koalas to be widely distributed and moderately abundant in uniform aged young (20–35 yr) plantation forests in management zones 1 and 2 while breeding female koalas were effectively absent from these areas.

Larger trees and denser, more uneven aged stands provide multiple potential benefits including: a) higher foliage biomass per tree; b) provision of suitable forks for sleeping; c) provision of scaffolding for easier access to terminal branches and outer foliage of understory trees; d) lower levels of toxins (FPCs) in some larger trees (Marsh *et al.* 2013); e) increased shade; and f) reduced risk of predation. Because of their large size koalas, unlike the much smaller greater gliders, are unable to support themselves on small outer branches and must break them off or pull them down from a larger branch to feed. Larger trees provide scaffolding for koalas to access young leaves on the growing tips and small outer branches of younger trees, especially shade-tolerant Tallowwoods and Grey Gums emerging from below the upper canopy. A high stocking or density of large trees also enables koalas to move from tree to tree by leaping, instead of coming to the ground, which carries an increased risk of predation by wild dogs which were abundant in Pine Creek State Forest. This is the only koala habitat in Australia in which the senior author has observed koalas leaping from tree to tree to move between trees while feeding. This behaviour has also been witnessed in Bongil Bongil National Park by Martin Smith (unpublished observations).

None of the preceding findings are consistent with the NRC (2021, 2022) conclusions that current native forestry regulations that permit the use of high intensity logging enable koalas to maintain their density 5–10 years after heavy harvesting. We have previously established that the findings of Law *et al.* (2022b) apply only to male koalas and not female koalas, but we also consider it likely that these findings for male koalas are partially or wholly an artefact of sampling problems associated with use of remotely deployed acoustic recorders. Because of their large area of coverage (about 25 ha) and long recording duration, there is a high likelihood that acoustic monitors failed to detect real declines in male koala density after logging due to detection of calls from koalas sheltering in unlogged filter strips and corridors retained within logged area and calls from dispersing or displaced male koalas simply moving through logged forest in search of new habitat. Furthermore, in their study Law *et al.* (2022b) equated logging intensity with m^3/ha of wood volume removed (from compartment history records), but this is not an accurate or rigorous measure of harvesting intensity because it does not record wood volume before and after harvesting or the volume of non-commercial tree stems felled and left on the forest floor. A high wood volume may be removed by a low intensity harvesting operation in a highly productive forest and low wood volume may be removed by a high intensity operation in a low productivity forest with a high proportion of culled, non-commercial species like Forest Oak and Grey Gum. Smith and Andrews (1997) examined relationships between recorded (compartment) logging intensity and forest structure in the Pine Creek State Forest and found no correlation between recorded logging intensity and existing forest structure. The only reliable way to measure logging intensity is to measure and report stand structure (the number of tree stems in incremental size classes) on the ground before and after logging. It is extremely unlikely that high intensity logging, such as that undertaken in the Pine Creek State Forest in recent years and shown in Figure 3, would have no impact on male koala density 5–12 years on because the 12 year old trees are too small for climbing, resting and avoiding predators, the diversity of tree species could be too low to sustain a diverse gut microbiome, and the biomass of foliage is insufficient to sustain a normal koala population density.

Law *et al.* (2022b) also claimed support for their findings from studies which found high koala densities in *E. globulus* plantations in Victoria (Ashman *et al.* 2020). However, these plantations represent an unnatural predator-free environment dominated by a known preferred koala food tree grown from stock of unknown genetic provenance that is likely to have been selected for growth and which may not have the capacity for chemical defense found in *E. globulus* in natural forests with a long history of koala browsing. The occurrence of koalas in these Victorian plantations provides no proof that koalas will inhabit planted regrowth forests regenerating after intensive clear-felling in forests of northern NSW. Law *et al.* (2022b) also claimed that "*current evidence suggests regulated harvesting with environmental protections could be compatible with koala conservation. For example, a radio-tracking study in the Pilliga forests of New South Wales (Kavanagh et al. 2007) found that koalas tolerate selective harvesting of shelter trees, at least in the short term (i.e. 6 months after harvesting*." The Kavanagh *et al.* (2007) study was carried out in a far western region where timber harvesting is highly selective, very low intensity and not representative of timber harvesting methods in the great majority of state forests within the koalas known range. The Pilliga Forests comprise a mixture of softwood (Cypress Pines) and hardwoods (*Eucalyptus* spp.) and harvesting removed only larger *Callitris glaucophylla*, which was not a preferred food tree of the koala in this study and comprised only about a quarter of stand basal area. A finding that cypress logging had no measurable impact on koalas is therefore both unsurprising and unremarkable.

Male koalas have been reported to utilize 7-year planted *Eucalyptus camaldulensis* of unknown provenance in the Gunnedah region of NSW, but only in proximity to remnant natural forest (Kavanagh and Stanton 2012) and in a region where dingoes are now absent. Law *et al.* (2022b) also claim that "*in tall hinterland forests of north-east NSW, a regional survey (Kavanagh et al. 1995) mostly recorded koalas in regrowth forest (< 30 years old), though the rate of detection was low and confounded with low elevation*". Hinterland forests of northeast NSW have until recently been selectively harvested at low intensity by removing only large sawlogs of merchantable tree species (due to lack of woodchip markets for smaller stems and species not suitable for sawlogs), and not by high intensity clear-felling for woodchip like that undertaken in southern NSW and Victoria. Kavanagh *et al.* (1995) did not measure actual logging intensity and forest structure in their survey sites but assumed that forests with a compartment history of several logging cycles had been "intensively" logged. Most forest in the Pine Creek area has been frequently logged on multiple occasions but harvesting prior to the mid 1990s removed only a few large, sound stems in each cycle and left forest structure in many areas complex, mature and uneven-aged. The highest quality koala habitats mapped as zone 4 and 5 in this study would have been classified as "intensively logged" in the study of Kavanagh *et al.* (1995). This forest cannot be reasonably described as <30 year regrowth. Also, as previously reported by Smith (2004), logging intensity was confounded with elevation in the study of Kavanagh *et al.* (1995) and the positive correlation between increased koala occurrence and logging intensity is likely to be an artefact of higher koala densities at lower elevations where logging cycles have been more frequent (but not necessarily more intense).

Law *et al.* (2022b) further claim, incorrectly, that the studies of Smith (2004) on koala density in the Pine Creek State Forest support their findings. Smith (2004) stated that "*Koala scats and vegetation in their home range are also correlated positively with the number of selective harvesting events*" but it cannot be concluded from this statement that koalas tolerate modern day high intensity clear-fell logging. Smith (2004) found that koalas were more abundant in forests subject to multiple low intensity events that created a complex uneven-aged structure. These events mostly included culling (felling or ringbarking) of large old dead, defective (crooked or piped) and living senescent trees and unmerchantable tree species in addition to selective removal of large sawlogs. This type of selective logging is no longer practised in the Pine Creek State Forest and cannot be equated with modern high intensity clear-fell logging which is more akin to land clearing and conversion of native forest to plantation (as shown in Figure 3). Smith *et al.* (2004) found a significant negative correlation between koala abundance and harvesting intensity as measured by the number of logged stumps/hectare in survey sites, and a significant positive correlation between the abundance of koala scats and the predominance of tree stems in larger size classes (>50 cm dbh).

Results of the current study confirm that koala density increases more than 10-fold along a gradient of increasing mapped habitat quality (zones 1–5), increasing forest age, and increasing structural complexity (as shown in photographs in Figure 2) in the study area. Habitat quality zoning effectively represents a gradient of increasing time since logging, decreasing logging intensity and increasing tree diversity and abundance of preferred food tree species (including *Allocasuarina*). The highest quality koala habitat includes forests characterized by a high density of trees across all size classes that have only been lightly selectively logged to remove large and old senescent trees, and that have a high diversity of locally preferred food trees tree species and an abundance of preferred koala food trees. The lowest quality habitat is characterized by young (20–35 year) structurally uniform trees often of a single, less preferred species regenerating after clear-fell harvesting and replanting (Figure 2). This is an artificial habitat generated by logging that does not sustain breeding female koalas and is likely to be a sink habitat (where mortality exceeds reproduction) for transient male and non-reproductive female koalas surplus to the resident breeding population. These findings indicate that continuation and expansion of high intensity logging across the remaining parts of the Pine Creek State Forest available for wood production has the potential to eliminate koalas from logged areas, destroy corridor links between remnant koala habitat in Bongil Bongil National Park and nearby upland conservation areas, and reduce the quality and integrity of koala habitat in the surrounding region including the proposed Great Koala National Park.

CONCLUSIONS

Koala habitat quality in the study area was found to vary by a factor of more than ten (from 0.02 to 0.2 koalas/hectare) over relatively short distances (100s of metres) in a complex mosaic determined primarily by variations in logging history, forest age and structure, and the diversity and abundance of locally important food tree species (including two non-eucalypt species in the genera *Allocasuarina* and *Syncarpia*). This habitat mosaic was mapped into 5 zones of increasing koala habitat quality by ground survey of forest floristic composition and structure in a 200 m grid across the study area. Male and female koalas utilized this mosaic differently with breeding females increasing strongly in abundance with increasing habitat quality while calling males were widespread across all habitats including plantation-like forests where breeding females were absent. These findings show that koala survey using call recorders that monitor male calls in the breeding season is not a reliable method for identifying koala habitat or response to logging. These findings also confirm that breeding female koalas are absent from uniform-aged regrowth forests that regenerated after clear-fell harvesting and replanting up to 35 years previously and are likely to be eliminated from forests that are intensively harvested on short rotations due to loss of floristic diversity and simplified structure.

Our findings contrast with reports that koalas are abundant in structurally simple, low diversity, plantation forests in Victoria. We account for this discrepancy by hypothesizing that koala density, diets and habitat preferences are determined by the duration and stability of local plant-koala interactions in response to past fire, hunting, and predation history. We propose that koala density in long term stable forest populations, such as those in the study area, is regulated at low levels (0.28/ha) by a combination of selected (fixed and genetic) and induced (temporary) increases in leaf toxicity and decreases in leaf nutrition that limit koala browsing to benign levels of about 1–2% of annual leaf production. Key characteristics of the koala population in the study area including large home ranges, frequent food tree changes, utilization of the full range of available tree species, and preference for areas of high food tree diversity, are consistent with a need to minimize browsing-induced toxicity in host trees by careful selection of individual trees and leaves that provide sufficient nutrients for breeding and lactation with minimal risk of predation. Koala population irruptions, over-browsing and abnormally high-density koala populations (>0.6/ha) occur primarily in areas where koalas have been introduced or reintroduced to planted habitats and natural areas where Aboriginal hunters and dingoes were historically present but are now absent and where food trees have not been selected for resistance to koala browsing pressure. While currently abundant, these populations may be unstable, require ongoing maintenance, or decline over the long term. Prior to European settlement the major stronghold of the koala is likely to have been low density, stable koala populations in remnant mid to low elevation tall wet forests in northeast NSW and south-east Queensland, including the study area, where the climate is mild and extensive wildfire is rare. These areas can be considered core areas for natural koala conservation where cessation of timber harvesting and increased reservation is a priority. Future studies of koala habitat for the purpose of local scale conservation and management need to consider a more complex array of variables including differences between the sexes, forest structure, the diversity and abundance of locally important food tree species, the effects of site variation and browsing history on the toxicity and nutrient levels of leaf samples and local tree species, and the capacity of local koala gut microbiomes to counter leaf toxicity.

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Data analysis, interpretation and report preparation for this study was undertaken by Andrew Smith following a request from John Pile to statistically analyse koala monitoring data collected in Pine Creek State Forest between 1996 and 1999. These data were voluntarily collected by John Pile and John Murray using a method developed in discussion with the senior author in 1996/97 and endorsed by a Scientific Working Group (including the senior author) appointed by the NSW Government to advise on koala management. Grid-based koala habitat survey and classification in the study area was carried out by John Pile and the resulting map was drafted by John Murray, on behalf of the Coffs Harbour Pine Creek Koala Support Group under contract to the NSW Government for the purpose of preparing a Koala Plan of Management (SFNSW 2000). John Pile also assisted in undertaking radio tracking studies of koalas in the study area overseen by Australian Museum Business Services. Andrew Smith is currently retired, has no employment or funding affiliations and undertook this work on a voluntary basis. Long term koala monitoring data for Bongil Bongil National Park collected by volunteers (including both authors) and coordinated by NSW National Parks and Wildlife Service (North Coffs Coast Area) were made available to facilitate interpretation of Pine Creek State Forest monitoring data. Dan Lunney, Martin Smith and two anonymous referees provided helpful comments on the draft manuscript, but the authors are solely responsible for any errors and the ideas and interpretations expressed in the paper.

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