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25th June 2014

Background:

My name is John Lemon and I have 30 years of experience in environmental research. I've lived on the Soil Conservation Research Centre at Gunnedah since 1988 and initiated a number of pioneering research projects during that time.

There are two areas I would like to address at this PAC forum: The koala component of the Environmental assessment report and the offset and rehabilitation plantings.

Koalas:

- The koala component is an extremely emotive topic in Gunnedah. The fact that the definitive number of 262 koalas on the Watermark site is tabled is of extreme concern.

- I was one of a number of OEH staff who commented on the initial Watermark KPoM in the EIS. We expressed our concern that one koala per 2ha was an extremely high population density. I note that this has been revised to one koala per 3.3ha – again a very high population density. From 2008 to 2011 we undertook a comprehensive koala research project in collaboration with the Liverpool Plains Land Management and their Executive Officer, David Walker. We put GPS tracking collars on more than 50 koalas during that time and found that the home range of the males was 25 – 30 ha and the home range of the females was 15 – 20 ha. This doesn't compute to the figures presented to the Watermark project.

- For many years, prior to the commencement of the 2008 project, I would undertake a 3km walk through the habitat reconstruction sites I established on the Research Centre from 1991 until 2005. These sites provide excellent koala habitat as well as providing habitat for a range of native species. Before 2008 I would see between 8 – 12 koalas per week, sometimes more, sometimes less. I've seen up to 10 koalas in a day and on one occasion I've seen and photographed 6 koalas in one tree. In the last 12 weeks I have seen just 3 koalas on my 3km monitoring circuit. One was dead, one was so afflicted by symptoms of chlamydia that I returned to capture her to have her euthanized by our local vet but she had disappeared. The other koala was too high in the eucalypt that I couldn't see if it was healthy or not.

- During our research project we had the drought and heatwaves of 2009. In November and December 2009 we had two serious heatwaves coupled with an ongoing drought. We know we lost 25% of the koala population across the Liverpool Plains – possibly more. Since then we have had the 2013 heat wave and the Warrumbungle bushfires coupled with a record maximum temperature of 46.9oC in Gunnedah on the 3rd of January 2014. This sequence of mortal blows to the koala population has had consequences that are still to be defined.

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- My personal opinion is that the koala population across the Liverpool Plains is in serious decline and that at this stage we could quite possibly have a population that has declined by up to 70% since 2008. Which leads me to my next point.

- I very much doubt if there are even 62 koalas on the Watermark site – quite probably significantly less. This is a very important point that needs to be considered in this process. If the koala numbers are less than the figure tendered – which is what I strongly suspect is possible – my recommendation is that a comprehensive day and night koala survey of the site be conducted prior to any on site works being undertaken – that is if the mining licence is approved.

- Finally, I suspect that koala relocation, as tendered in the initial KPoM and 2014 Environmental Assessment Report, will be minimal at least. The reason for this will be the low number of koalas on the site. If there is a requirement for any relocations I have what I believe could be a suitable solution to this potential concern.

Offset/Rehabilitation plantings

- The Watermark site has similar topography and soil types to the Gunnedah Soil Conservation Research Centre. Basically it was cropping country in the 40's, 50's and 60's before it reverted to grazing when cropping was no longer a profitable option.

- In 1991 I established Habitat Reconstruction sites at the Centre which continued until 2005. In 2000 this methodology was extended to sites across the sheep/wheat belt of NSW.

- I initiated biodiversity audits in 1999 at the GRC sites which continue to this day. Species such as koalas, Glossy Black Cockatoos, Speckled Warblers, Painted Honey-eaters, Narrow-nosed Planigales and Common Dunnarts have re-colonised these sites.

- My take home message is this. With considered planning and implementation you can achieve significant biodiversity benefits from what was previously a degraded cropping/grazing landscape. Our research and outcomes over the past 23 years prove that this is not only possible - it can be done. These same principles can be applied to the Watermark site with equally positive results if done as part of an informed, consultative and structured methodology. It just takes time and commitment to make sure it happens.

References:

Daniel Lunney, Mathew S. Crowther, Ian Wallis, William J. Foley, John Lemon, Rob Wheeler, George Madani, Corinna Orschreg, Joanna E. Griffith, Mark Krockenberger, Melissa Retamales and Eleanor Stalenberg: **Koalas and climate change: a case study on the Liverpool Plains, north-west New South Wales.**

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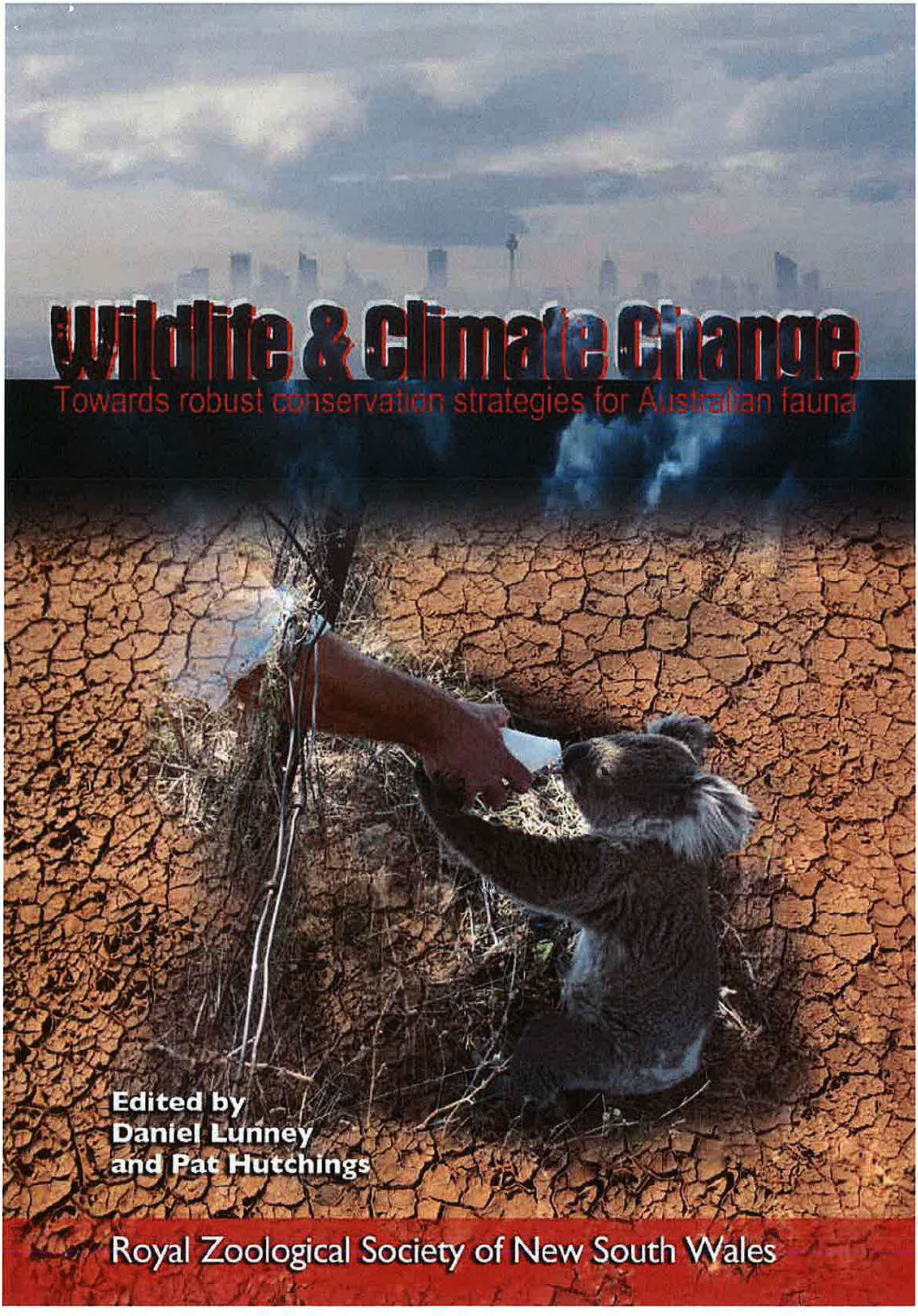
D Lunney, J Lemon, MS Crowther, E Stalenberg, K Ross and R Wheeler: **An Ecological Approach to Koala Conservation in a Mined Landscape.**

John Lemon, Warren Martin, Brian Wilson, Chris Nadolny and Daniel Lunney: **Habitat Reconstruction at Gunnedah Research Centre, Gunnedah. New South Wales.**

Poster: **Climate Change and Koala Populations: The likely impact of rising levels of carbon dioxide and heat stress with implications for adaption**



Wildlife & Climate Change

Towards robust conservation strategies for Australian fauna

Edited by
Daniel Lunney
and Pat Hutchings

Royal Zoological Society of New South Wales

Koalas and climate change: a case study on the Liverpool Plains, north-west New South Wales

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ABSTRACT

Koalas are prime candidates to study the impact of climate change because they are specialised folivores and lack any ready means of avoiding weather extremes. Koalas are widely but patchily distributed throughout eastern mainland Australia. Efforts to protect them from landscape-scale threats have been identified in the *NSW 2008 Koala Recovery Plan*, the 2010 NSW *Priorities for biodiversity adaptation to climate change* and the *2009-14 National Koala Conservation and Management Strategy*. The statements in the formal strategies and recovery plans identify a number of problems, two of which we address in this paper. The first problem is that of extreme weather and the second is the change of leaf quality from rising levels of carbon dioxide. This paper capitalises on our field study in Gunnedah, in north-west NSW, which examined a 1990s success story where the local koala population benefited from the plantings of trees and shrubs to hold down the water table in the face of a rising salinity crisis. In late 2009, heatwaves killed an estimated 25% of the Gunnedah koala population. This foreshadows how increased climate variability will impact on koala populations. In 2008, chlamydiosis – a disease causing infertility – had been established as being present in the Gunnedah population. The likely spread of this disease throughout the Gunnedah koala population presents a further challenge to wildlife managers in the context of a changing climate. The potential indirect effects of global climate change – how increasing concentrations of atmospheric CO_2 may reduce the availability of the nutrients in *Eucalyptus* foliage to koalas – is described and the implication drawn that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas. The Liverpool Plains are among Australia's prime agricultural landscapes where the conservation of biodiversity occurs largely on private land. Consequently, we need to integrate climate change adaptation with rural land management and restoration practices. The research demonstrates the contribution from the cross-disciplinary links. It adds to our ability to monitor sustainable native fauna populations and threatened species by distinguishing among the multiple causes of population change, and it can also be viewed as a pilot demonstrating the value of longitudinal wild population disease monitoring.

Key words: koala, *Chlamydia*, carbon dioxide, environmental plantings, land restoration, Namoi Catchment Management Authority, heatwave, radio-tracking, fauna monitoring.

Introduction

Koalas *Phascolarctos cinereus* are specialised, folivorous arboreal marsupials that do not go into torpor, fly, or shelter in hollows, and lack any ready means of avoiding weather extremes. This makes them valuable candidates to study impacts of climate change. This paper draws on our field study of koalas in Gunnedah in north-west New South Wales (NSW), to not only examine this proposition, but to progress to the next step of considering how we, as koala managers, can adapt our strategies to help the koala population cope with predicted climatic changes. The koala already faces a powerful set of threats, such as loss of habitat and fragmentation of what remains, disease, fire, and the impact of losses from dogs and vehicles. Climate change will compound these issues, accelerate adverse changes and demand a reappraisal of our approach to koala management. The koala is not unique in this predicament, but it is symbolic of the impact that can be expected on a wide range of species.

Pp 150 - 168 in *Wildlife and Climate Change: towards robust conservation strategies for Australian fauna*, edited by Daniel Lunney and Pat Hutchings, 2012. Royal Zoological Society of NSW, Mosman, NSW, Australia.

The structure of this paper examines climate change by teasing apart the separate threats of heatwave, disease, declining leaf nutrition and drought to a koala population across a prime agricultural landscape. We need to consider these impacts in the context in which we manage koalas at a local, state and federal level. Thus we begin with the conservation and management context which alerted us to the issues and empowered particular actions to be taken. We provide a field account of heatwaves that occurred in 2009 during our study of koala movement patterns and tree selection on the Liverpool Plains. We then provide a review of the likely physiological effects of elevated CO_2 on foliage composition, as well as the effects that heat and drought will have on the feeding behaviour, and thus the potential impacts on free-living koala populations. The interaction between the field data, theoretical projections in relation to climate change, and the management context allows a constructive approach to be taken for adaptive management of this iconic species.

Managing koalas for climate change - government policies

The formal policies put in place by local, state and federal governments to manage wildlife, and specifically koalas, in the context of a changing climate, provide both the means of studying the problems and the actions to be taken based on this research. The main instruments and policies, summarised below, to provide a unified context for the different strands of research covered in this paper, and it is through these mechanisms that solutions will be attempted.

New South Wales

i) The *Threatened Species Conservation Act 1995*, "Anthropogenic Climate Change" listed both as a key threatening process, and the koala, as a threatened species. There is also a *2008 NSW Koala Recovery Plan* (DECC 2008). In the plan, the following statement appears under the heading 9.2.8 *Severe weather conditions*:

"The degree of impact of natural disasters such as drought, heatwave or flood on koala populations is influenced by the quality and quantity of available habitat. These severe climatic events are expected to increase in both occurrence and intensity as a result of climate change impacts. For example, in south-western Queensland, a heatwave and drought in 1979–80 resulted in the death of 63% of the koala population in the area (Gordon et al. 1990). The animals which survived were those living in good quality habitat along permanent watercourses. In the sub-optimal habitat away from permanent water, the trees lost their leaves and the koalas were left with no food or shelter (Gordon et al. 1990).

Studies in other areas have demonstrated that during drought conditions, koalas move from drier areas to the vegetation along creeklines and rivers where soil moisture is higher (Reed and Lunney 1990). These examples illustrate the value of refuge areas when conditions become unfavourable. The widespread clearing that occurred with European settlement was primarily in the more fertile areas along watercourses; areas that would have provided refuge habitat. The loss of large areas of this vegetation has reduced the ability of koalas to survive extreme weather conditions.

Other than drought and fire, harsh conditions such as storms and snow falls have killed koalas (Reed and Lunney 1990). Such events are infrequent however, and their impact on koala populations is relatively small. These impacts may potentially increase as a result of climate change."

These descriptions of the problems are followed by a set of objectives and actions:

"Objective 1: Conserve koalas in their existing habitat… Specific objective 1a: Identify and conserve habitat important for koala conservation."

"*Action 1.3.* DECC [Department of Environment and Climate Change now Office of Environment and Heritage, OEH] will undertake and encourage other researchers to undertake population studies of koalas in a range of habitats in relation to a range of issues such as fire, drought, dogs, cars, habitat fragmentation and climate change. This action may include rural surveys (e.g. Gunnedah), peri-urban surveys (e.g. Campbelltown) and repeat surveys for already-surveyed areas. The aim of such work is to determine density, population size and trends in population dynamics."

ii) The DECCW [Department of Environment, Climate Change and Water now OEH] (2010a) statement *Climate Change Impacts New England/North West NSW*, projects that regional climatic changes by 2050 will be a moderate decrease in winter rainfall and a slight to moderate increase in rainfall in other seasons. Due to increased temperatures, drier conditions are projected, particularly in winter and spring. Days are projected to be hotter over all seasons, with the greatest warming in winter and spring (2 to 3°C). Nights are also projected to be warmer, with mean minimum temperatures projected to increase by 2 to 3°C in the east of the region, and slightly less in the west.

The DECCW (2010a) statement also notes that higher temperatures and drier conditions are very likely to have a major impact on biodiversity, and that climate change is likely to place additional pressures on those ecological communities that are already stressed due to fragmentation and may be less resilient to disturbances. The report states that fauna is likely to be affected by habitat loss, long hot spells and reduction in key habitat resources such as hollow-bearing trees and nectar. Increased fire frequencies are likely to lead to widespread changes across many ecosystems.

iii). The DECCW (2010b) NSW *Priorities for biodiversity adaptation to climate change* is a Statement of Intent in response to the listing of Anthropogenic Climate Change as a Key Threatening Process under the NSW *Threatened Species Conservation Act 1995*. This policy document recognises that a range of management strategies and mix of actions from the species level to the landscape level are needed, and that while it will be possible to build on many existing conservation programs, some adjustments and new approaches will also be necessary. Of the four key priority areas for which measures will be taken, two are most relevant to koalas on the Liverpool Plains, namely: Enhancing our understanding of the likely responses of biodiversity to climate change and re-adjusting management programs where necessary in light of this information, and Increasing opportunities for species to move across the landscape by working with partners and the community to protect habitat and create the necessary connections.

b) Commonwealth

At a Commonwealth level, the *National Koala Conservation and Management Strategy (2009-2014)* identifies both the threats and the actions to address them. The implementation of that strategy is now underway. Under the heading "6.7 Climate change", the following text is presented: "The impacts of climate change on koalas are already apparent, particularly in western Queensland and New South Wales. They include: changes in the structure and chemical composition of koala food trees; changes in the composition of plant communities and the range of important habitat species, including food and shelter trees; increased frequency and intensity of drought; increased frequency and intensity of wildfire; sea level changes which may affect the habitats of coastal and island populations; changes in average temperature, rainfall and humidity levels with consequent impacts on the extent of areas capable of sustaining koalas; and contractions in the distribution of koala populations."

"Climate change is likely to compound existing stresses of habitat loss and fragmentation, leading to higher risks from disease, and may also increase the risk of injury by dog attacks and vehicles as koalas move across the landscape in search of food."

In 2010, the Senate initiated an enquiry into the status, health and sustainability of Australia's koala population (Commonwealth of Australia 2011). The range of submissions and transcripts of the hearings show a widespread interest in the future of Australia's koala populations and the impact from a suite of threats including climate change. At the time of writing, there have been no reports from the committee undertaking the enquiry, although it can be expected to reflect the widespread concern for both current and future threats, including climate change.

The 2009 heatwaves in Gunnedah

The second strand of this paper draws on our current field study in Gunnedah, in north-west NSW. The team from the Office of Environment and Heritage (OEH), in conjunction with the University of Sydney, is capitalising on a successful 1990s program which planted trees and shrubs throughout Gunnedah, initially to hold down the water table in the face of a rising salinity crisis. Gunnedah is on the Liverpool Plains, in the Namoi Catchment Management Area in the Murray-Darling Basin. The project in Gunnedah included fitting free-ranging koalas with VHF/GPS collars (Sirtrack®, Hawkes Bay New Zealand). The GPS units recorded the location of the koala at 4-hour intervals, starting at 5 pm on the first day of recording, and continuing for a maximum six months. The aim of this project was to investigate koala movements to determine tree choice, with particular reference to their use of the environmental plantings. Extreme weather – heatwaves in late 2009 – introduced a major climate change element. This was examined in relation to: death of koalas during the heatwaves; reduced breeding rate; and the disease chlamydiosis becoming visibly manifest in the local koala population.

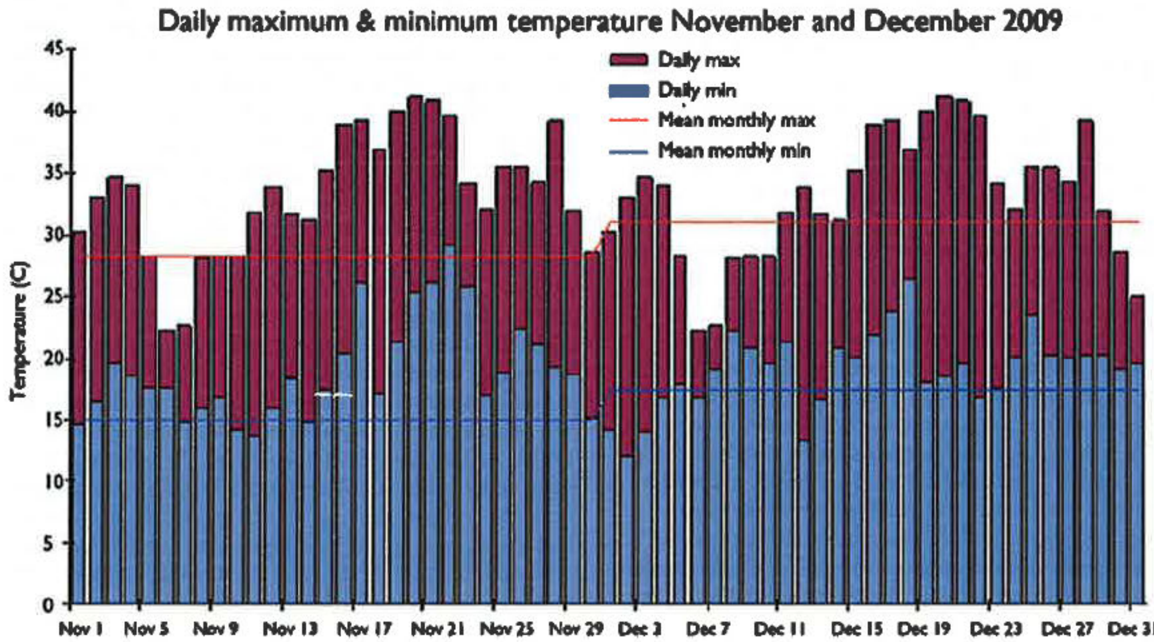

Figure 1. Daily maximum and minimum temperatures for November and December 2009 showing the succession of heatwaves in Gunnedah near the end of a long drought. The data were obtained by the Australian Bureau of Meteorology from the Gunnedah Resource Centre, where many of the koalas were captured. The monthly long-term averages of minimum and maximum are the average since 1948. The important feature of the above-average high temperatures in November and December is that they occur in a succession of days, rather than just isolated days. Further, the night temperatures are also above-average, and again occur in strings of days.

Koala deaths

There were two extended heatwaves in November and December 2009, just before the end of a long drought (Figure 1). We witnessed the visible and immediate impact on the koalas of the heatwave of December 2009. Collectively, the accounts of the behaviour and distress of the local koalas present a compelling story of the impact of a heatwave during a drought, i.e. when there is no free water.

One koala (not one of our collared study animals) was clinging low on the trunk in a Kurrajong *Brachychiton populneum* in the Gunnedah Resource Centre, 5 km from the town of Gunnedah. Kurrajongs are moderately tall (5 to 20 m high) with a dense canopy of shiny green leaves and a thick, smooth, grey-barked trunk. The pale-coloured soft, spongy wood has no commercial use (Milthorpe and Cunningham 2005), but the low branches are easily reached, making it an excellent domestic stock fodder tree during drought. The significance of Kurrajongs and other trees providing shade rises in importance in the light of our understanding of koalas endeavouring to avoid heatwaves. The koala left its tree to accept water that we offered it, initially by spraying water on its nose, then via the nozzle on the spray-gun. Our sequence of photos of this remarkable event tells part of the story of the impact of a heatwave (see Appendix). After the koala felt the water on its nose, it then sprinted to John Lemon, who was holding the spray-gun. It clasped his hand to stop John Lemon withdrawing the bottle to refill it. The koala climbed through the fence to pursue John Lemon in its quest for the water bottle. What is so remarkable is that this koala would, in any other circumstance, have quickly climbed the tree on our approach. It was manifestly desperate for water.

A local farmer (Rob Frend) reported that five of a group of about 20 koalas known on his property (Dimberoy) were found dead on the ground during the heatwave in December 2009. Another local landowner counted 12 koalas dead on his property in the same month. Two koalas that were not radio-tracked for this study were found moribund at the base of trees on two different properties (Dimberoy and Turon Park) and required veterinary intervention in the form of intravenous fluid therapy. The larger of the two koalas (ca 8 kg) required 2 litres of Lactated Ringer's solution to survive, while the smaller (ca 5 kg) required 1 litre of this solution. These volumes totalled approximately 20-25% of their body weight. Severe dehydration (> 10%) is commonly associated with death in other species (Sherman *et al.* 1983) and death would presumably have occurred in these animals without intervention. These two animals recovered and were released, but were not radio-tracked.

Of our 15 koalas radio-tracked during summer 2009, two suffered from dehydration and needed veterinary treatment (intravenous fluids for rehydration as described for the two koalas above that were not in the tracking program). Further, two radio-tracked koalas were found dead in this time period, which we attribute to dehydration, there being no other obvious explanation. If these figures are indicative of the local population, then at least a quarter of all the Gunnedah koala population would have perished in these heatwaves. As the local veterinarian, David Amos, commented at the time, "The local koalas will be dropping like flies." This view was quite clear to the local landowners whose stock were also suffering from the heatwave. The combination of drought and heatwave had proved to be lethal to the Gunnedah koala population.

In late December 2009, it rained in Gunnedah as the drought broke. A common observation by the residents of Gunnedah was that koalas were drinking in pools at the edge of the road (J. Lemon pers. obs.). This was so remarkable that photos were included in the local press, the *Namoi Valley Independent* (22/12/2009, Appendix). Reports and photos of town koalas drinking from dog bowls during the drought were also made in the *Namoi Valley Independent*. Since water was freely available to koalas living in urban areas of Gunnedah such as in dog bowls, the impact of the drought on the koala population as a whole may not been recognised by the town residents. However, the severity of the drought and the heatwave on koalas had been noticed by people living on rural properties.

Reduced koala fertility and population size

In the spring (October) of three successive years (2008-2010), we caught koalas with the primary aim of fitting them with radio-tracking/GPS collars. At each of the three spring catching and collaring field trips, we identified whether females had young on their back and inspected their pouches to check for the presence of young. We defined the fertility of the population as the proportion of females with dependent young, irrespective of the age of the offspring. The results show that the percentage of young was similar in 2008 and 2009, but it had sharply declined by October 2010 (Table 1). Most females had young, despite the drought, in October of 2008 and 2009. By October 2010, the drought had broken and the Liverpool Plains were visibly green. The low level of fertility is interpreted here as a delayed impact of the drought and the heatwaves in November and December 2009 on the health and condition of the koalas. In addition, koala admissions to the local veterinary hospital had dropped from about 4 per week, to about one per month over the last three years, i.e. about a 16-fold decline (David Amos pers. comm. April 2011). This decline may indicate a fall in size of the Gunnedah koala population.

Table 1. Number of female koalas with young caught in Gunnedah.

Date	Number of adult females	Number of females with young	Percent females with young
October 2008	8	6	75%
October 2009	9	8	89%
October 2010	10	4	40%

Disease

In 2010, the health of the koalas sampled from the population appeared to have declined, and not only was the proportion of females with young lower in 2010 than in 2008 and 2009, but chlamydiosis, an infectious disease impacting fertility, was confirmed in this population and was clinically evident. Gunnedah had previously been considered (anecdotally) to be free of this disease.

In October 2008 and 2010, there was a detailed veterinary inspection and sampling of each koala that went into the collaring program; with a particular emphasis on the status of chlamydial infection and clinical disease in the population (see photos in Appendix). The anecdotally-reported status of Gunnedah's koalas being *Chlamydia*-free had attracted our attention. The polymerase chain reaction (PCR) results for 2008 show that 2 koalas of 12 were carrying *Chlamydia pecorum* (8%), however there was little evidence of clinical disease at this time, with one animal showing a mild to moderate conjunctivitis consistent with chlamydiosis.

Preliminary real time PCR results in 2010-2011 suggest an increased prevalence of chlamydial carriage in the population (approximately 43%, unpublished data). Further, clinical disease, previously undescribed in Gunnedah koalas (David Amos pers. comm.) was now evident in both males and females. Of particular interest was the finding that older females, caught in April 2011, showed no evidence of recent breeding, a situation commonly encountered in populations where clinical urogenital chlamydiosis is a frequent occurrence (McLean 2003). In particular, one animal exhibited signs of rump pelage stain and incontinence most frequently associated with structural chlamydiosis, a condition associated with infertility (McLean 2003; Higgins *et al.* 2005) and one large male had clinical bilateral chlamydial conjunctivitis confirmed by real time PCR (see Appendix), which can cause blindness impacting survival.

Of primary importance is that, in October 2010, a large male koala was conspicuously clinically *Chlamydia* positive. He was taken into care in Waterways Wildlife Park, managed by carer Nancy Small, under the authority of David Amos and treated with chloramphenicol (60 mg/kg subcutaenous injections twice daily for 42 days) and released after confirmation of cure by real time PCR. He entered the radio-tracking program, and was recaught in April 2011, at which point there was no clinical evidence of recurrence of disease.

Climate change and koala physiology: a review

The potential physiological effects of elevated CO_2 on the nutritional ecology of koalas

Increasing concentrations of atmospheric CO_2 may reduce the availability of the nutrients in *Eucalyptus* foliage to koalas. This change in leaf quality will affect all koala populations across their range, from tropical Queensland to southern Victoria. However, the management of koalas will be at the population level. The impact of climate change on individual koala populations can be expected to vary with the local conditions. In addition, 53% of *Eucalyptus* species currently have ranges spanning less than 3°C of mean annual temperature, with 41% having a range of less than 2°C, and 25% with less than 1°C (Hughes *et al.* 1996). Twenty-three percent of species have ranges of mean annual rainfall that span less than 20% variation (Hughes *et al.* 1996). The conclusion drawn is that, "within the next few decades, many eucalypt species will have their entire present-day populations exposed to temperatures and rainfalls under which no individuals currently exist" (Hughes *et al.* 1996). Since koalas are dependent upon a few species of eucalypt within any one location, the impact on local koala populations can be expected to be marked and wide-ranging. Land managers and wildlife managers are urged to pay attention to any proposed environmental plantings for koala habitat. Since each eucalypt species has a different bioclimatic envelope, the impact of climate change will be different for each local koala population.

Although several studies indicate how elevated CO_2 concentrations influence the chemical composition of eucalypts (see below for details), the utility of this knowledge for understanding populations of koalas is hampered by our poor understanding of the links between nutrition and population dynamics of free-living herbivores. The typical approach is to form ratios of the concentrations of foliar nutrients, especially nitrogen (positive leaf attributes) and potentially refractory substances including fibre, total phenolics and tannins (negative attributes). These ratios, however, have not provided a reliable tool for predicting the size and density of animal populations (Wallis *et al.* 2011). Part of the reason for this failure is that animals respond to the concentration of digestible (= available) nutrients rather than the total amount.

"Available N" is a new *in vitro* measure described by DeGabriel *et al.* (2008) that integrates the effects of total N, the protein binding effects of tannins and the digestibility of the foliage into a single measure that can be easily interpreted. There are several reasons why measures of total concentrations of a nutrient do not reflect what is available to animals, but in eucalypts the major reason is that tannins naturally present in the leaves can bind with dietary proteins and make them unavailable for the digestive enzymes of mammals (Wallis *et al.* 2011). The ideal way to quantify this would be to make multiple measures of the response of captive koalas to leaf that varied in the concentration of tannins, but this is very time consuming so an *in vitro* procedure is used instead. *In vitro* procedures have advantages of speed, however differences in the physiology of different species of marsupials (e.g. koalas and common brushtail possums) can mean that the results of *in vitro* measures should be seen as a guide to possible effects rather than absolute (Wallis *et al.* 2011).

If we can understand how natural variations in nutrition affect population dynamics of marsupials in the field, then we may be able to predict how changes in foliar nutrients due to climate change might affect those populations. In an important study, DeGabriel *et al.* (2009) compared the influences of total nitrogen (N) and available N on reproduction by common brushtail possums *Trichosurus vulpecula* inhabiting savannah woodland near Townsville.

They found a strong relationship between the mean available N concentration of the foliage within home ranges of individual female possums and (i) the likelihood of breeding at each opportunity and (ii) the growth rate of the pouch young. In contrast, total N did not relate to either measure of reproduction. The importance of DeGabriel *et al.*'s (2009) work is that it was among the first to link plant defence, plant nutrients and the reproductive performance of individual animals. Mothers with ranges that had higher mean foliar concentrations of available N produced more young that grew faster (Figure 2). If these patterns reflect how populations of other folivorous marsupials respond to changes in the availability of foliar nutrients, then we should be better able to predict how changes in foliar nutrients associated with elevated CO_2 might affect populations of koalas.

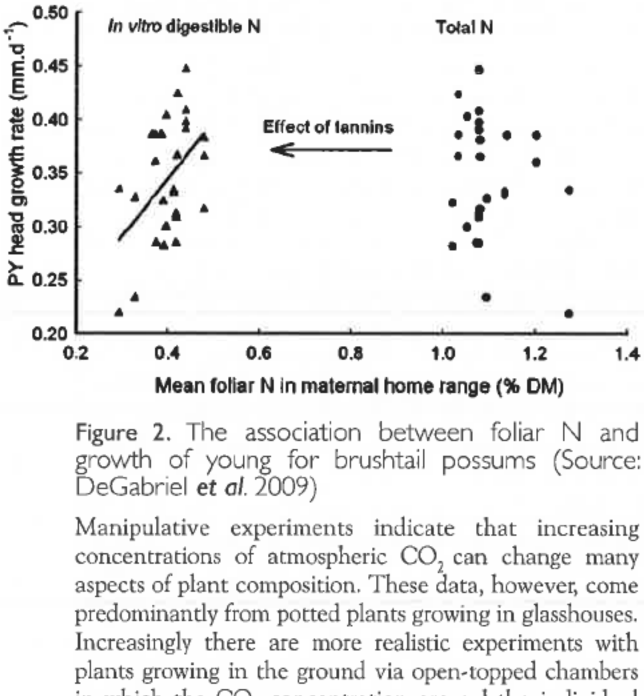

Figure 2. The association between foliar N and growth of young for brushtail possums (Source: DeGabriel **et al.** 2009)

Manipulative experiments indicate that increasing concentrations of atmospheric CO_2 can change many aspects of plant composition. These data, however, come predominantly from potted plants growing in glasshouses. Increasingly there are more realistic experiments with plants growing in the ground via open-topped chambers in which the CO_2 concentration around the individual plant is controlled, or via Free Air Carbon Dioxide Enrichment (FACE) experiments. Eucalypts are now being studied in both open-topped chambers and a FACE array at the Hawkesbury Forest Experiment at Richmond (Barton *et al.* 2010).

Although no study has looked specifically at the effect of elevated CO_2 on available N, studies by Lawler *et al.* (1997) of *Eucalyptus tereticornis*, Gleadow *et al.* (1998) of *E. cladocalyx* and Arlene McDowell (unpublished) of *E. ovata* measured some elements of available N in plants growing at elevated and current atmospheric CO_2 concentrations. In each study, foliar N in plants subjected to elevated CO_2 concentrations (690-750 ppm) declined by about 30% relative to controls (350-370 ppm, current concentrations are about 390 ppm). Lawler *et al.* (1997) found that the concentration of foliar condensed tannins increased by about 30% and both Gleadow *et al.* (1998) and McDowell (unpublished) found that foliar concentration of total phenolics also increased by about 30% relative to controls.

Taken together, these results suggest that, largely due to declines in total N and, to a lesser extent, a rise in the concentrations of tannins and other phenolics, available N should decline in plants growing under elevated CO_2. This suggests that aspects of leaf chemistry known to be associated with reproductive output of free-ranging folivores will change as atmospheric CO_2 concentrations rise. Thus, we could infer that elevated CO_2 will lead to significant declines in the populations of folivorous marsupials such as the koala. However, below we describe several caveats associated with this conclusion.

DeGabriel *et al.* (2009) demonstrated that even small changes in available N corresponded with large changes in reproductive success of the females and in the growth of their young. Studies of other species, including koalas, or at sites of higher fertility, may not show such steep relationships and so equivalent changes in available N may not have the same influence on reproduction. This suggests erring on the side of caution when extrapolating from a single population of common brushtail possums to a wider community of folivores. Second, we emphasize that the published data describing the effects of elevated CO_2 on eucalypts all comes from glasshouse work. Plants growing in more realistic settings possibly respond differently, with lower reductions in foliar N and these studies may also reveal the effect of drought and elevated CO2 in the water content of leaves. The results of the Hawkesbury Forest Experiment will be of great interest in this regard. Finally, in all three glasshouse studies, there were variable effects of elevated CO_2 on other secondary metabolites that could influence koala feeding. McDowell (unpublished) found no effect on foliar formylated phloroglucinol compounds (FPCs) in *E. ovata* and Gleadow *et al.* (1998) found no change in the concentration of foliar cyanogenic glycosides, although they comprised a significantly greater proportion of total N. In no study did elevated CO_2 alter foliar terpenes. The pattern of significant changes in tannins and total phenolics, but no effect on terpenes and FPCs, agrees with what we know about the relative genetic and environmental control of these classes of secondary metabolites. We cannot discount the possibility that gene-environment interactions will affect these patterns (Andrew *et al.* 2010) at different sites and in different species of folivores.

Nonetheless, what we know suggests that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas.

A physiological quandary – koalas, leaves and water

In addition to the likely changes in leaf chemistry caused by increasing concentrations of atmospheric CO_2, climate change models also predict that eastern Australia will be hotter and drier. Animals have differing reactions to heat stress, which often involves dehydration. Insights into the likely effects on koalas come from studies of Maloiy *et al.* (2008), who studied the interaction between intermittent heat stress and dehydration in several domesticated and wild ruminants from arid and semi-arid regions. Some, such as zebu cattle and Turkana goats, depressed their feeding by more than 40% when exposed to intermittent temperatures of 12 hours at 22° C followed by 12 hours at 40° C compared to a stable temperature of 22° C. Other species, such as Grant's gazelle and Oryx, did not further reduce their feeding when dehydrated and exposed to 40° C. In contrast, when dehydrated by 15% of body mass, all species ate less at an ambient temperature of 22° C. The authors concluded that selection has resulted in species that vary widely in their tolerances of heat and dehydration and that some show a remarkable resilience in maintaining digestive efficiency under these conditions. Research on different breeds of cattle suggests that animals that withstand heat stress show little increase in body temperature and little decrease in blood triiodothyronine (T3) hormone concentration (Pereira *et al.* 2008).

Animals well adapted to drought and heat can maintain their feeding partly because they can withstand the increase in metabolism due to the heat increment or specific dynamic action (SDA) of food – the energy expended in digesting and absorbing a meal and, for many animals including the koala, the cost of detoxifying secondary plant chemicals. Krockenberger (2003) estimated an SDA in koalas of 49 kJ per day, or 3% of total metabolism, much lower than that predicted (178 kJ; 10% of metabolism) for a 6 kg mammal (Secor 2009). Whatever the value, the important point is that feeding increases metabolism and requires the animal to dissipate heat. Ellis *et al.* (2010) suggested that koalas might be able to alter passage rate so that they did not digest the energy and nutrients of the leaves but just obtained water. However this is not consistent with what is known of the physiology of the koala. Although large digesta particles pass from the gut of the koala faster than do small particles, the process that effects this separation occurs after extensive digestion in the small intestine. In addition, mammals cannot produce faeces with less than about 55% of the mass being water because of physiological limits to water absorption in the colon. Thus ingested leaf that remained substantially undigested as suggested by Ellis *et al.* (2010) would lead to faecal water losses equivalent of the water gained from ingesting leaves.

We know little about the physiological reactions of koalas under field conditions of heat stress and dehydration. Clues, however, come from the population crash some 30 years ago along Mungalalla Creek in southwestern Queensland, mentioned earlier in this paper. In this forerunner to the 2009 Gunnedah incident reported here, Gordon *et al.* (1988) reported 63% of koalas dying. The conditions had a marked differential effect on animals. Those dying were dehydrated, in poor condition, had increased tick burdens, and inhabited places where the creek was dry and trees were in poor condition. In contrast, many larger, older animals remained in good condition and inhabited areas near permanent waterholes where the trees also remained healthy. This suggests a link between the water content of leaves and the health of koalas. Evidence from some of the Gunnedah koalas which actively sought water, raises the possibility that koalas drank from the waterholes, but the paucity of literature reports of koalas drinking suggests this is probably rare.

Thus, one key factor separates koalas from the various ruminants mentioned previously: koalas obtain most of their water from food and probably rarely maintain their hydration through a source of drinking water. The result is that hot and dry conditions push the koala into a physiological corner with no apparent exit. First, it is likely that leaf moisture declines during droughts, as shown by the Mungalalla Creek episode, where many trees adjacent to dried-up watercourses shed leaves. This is critical given that in more moderate conditions Ellis *et al.* (1995) observed koalas eating wet leaves and suggested they may coordinate feeding to maximise their ingestion of this source of water. Second, it is likely that the animal's water requirements increase during heat stress through evaporative heat loss, while it has minimal scope for conserving water through concentrating urine or dehydrating faeces. Thus, the animal may need to eat more to satisfy its water requirements. Eating, however, causes an increase in metabolism through SDA, placing the animal in a futile cycle: it must dissipate the additional heat by increasing its respiration rate with resultant evaporative water loss.

We can depict this scenario in the geometric framework of Simpson and Raubenheimer (1995) using two axes, to represent nutrients and water, the intersection of which represents the koala's target for nutrients and water (Figure 3). Line C represents the physiological quandary that we can expect during droughts. The leaves are drier and the koala can meet its water needs only by ingesting more nutrients. This may be possible although Krockenberger (2003) suggested that under normal conditions koalas may already be approaching the limits of gut capacity. If, however, a heatwave coincides with drought, then the heat generated by SDA may prevent a koala from eating more food and thus it will dehydrate.

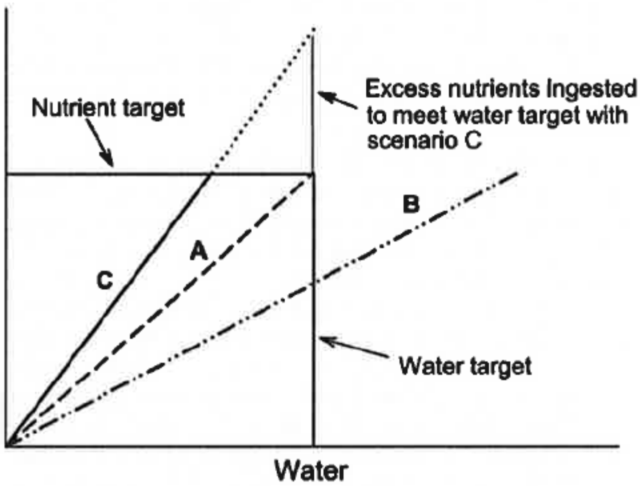

Figure 3. In this scenario, line A represents leaves containing the appropriate concentrations of both nutrients and water, so the animal will satisfy both with a minimal amount of food. In contrast, line B represents leaves with a high concentration of water so by the point that the koala meets its nutrient requirements it has well exceeded its needs for water. This is not a problem: it readily excretes the excess water as urine or moister faeces. Line C represents the physiological quandary that we can expect during droughts.

How might koalas excise themselves from this physiological quandary? In the absence of drinking water, including wet leaves, we would expect koalas to stop eating during very hot weather (or eat only at night depending on temperatures) when SDA will be less likely to cause heat stress. In summer, when nights are much shorter, this leaves a narrow window for feeding. An alternative strategy is for koalas to seek the coolest environment available, as evidence suggests they do by seeking particular trees in which to rest (Ellis *et al.* 2009), and attempt to endure a heatwave (perhaps by withdrawing water from the gut to maintain vital processes). The results from both Gunnedah and Mungalalla Creek suggest this may be true because in both cases dying koalas were severely dehydrated and in poor condition.

Discussion

An immediate and deleterious impact

From our radio-tracking data and observations of dehydrated koalas, and landowners' accounts of dead koalas where we were radio-tracking, we estimate that about a quarter of the Gunnedah koala population perished in a matter of weeks during the November and December 2009 heatwaves. Thus a combination of drought and heatwave proved to be lethal. The frequency, severity and duration of drought and heatwaves are forecast to increase under the climate change scenarios covering most of the range of the koala (e.g. DECCW 2010a, 2010b). From 2008 to 2010, the prevalence of the disease *Chlamydia* rose, foreshadowing increased rates of mortality and infertility. Simultaneously, in 2010, the birth rate fell and there were indications in early 2011, from admissions to the local veterinary surgery, that the koala population had declined sharply since 2008. The conclusion drawn from this sequence of events is that the Gunnedah koala population suffered an immediate and deleterious impact from heatwaves during the drought of 2009.

The shock of this conclusion is in its contrast to our 2006 state-wide survey of koalas in NSW (Lunney *et al.* 2009), in which Gunnedah emerged as an area with a koala population that had expanded, contrary to state trends, since the previous state-wide survey 20 years earlier. Given that the koala is a threatened species in NSW, the finding of the 2006 survey drew us to examine the Gunnedah population. We particularly focussed on the value of the environmental plantings of trees in providing additional koala habitat, especially plantings since 1990 when the "Bearcare" soil conservation initiative was launched (Smith 1992). Preliminary analyses of koala movement patterns indicate that the plantings have contributed to the expansion of the Gunnedah population; however we can now add that future tree plantings for koalas will need to consider changed climatic conditions. Thus, we need to adapt a successful environmental-planting program to cope with the projected impact of climate change. National and NSW State strategies and recovery plans have recognised this need in principle. This Gunnedah study puts that need into sharp relief.

The inevitable long-term impacts

The koala already faces a powerful set of threats from loss of habitat, disease, fire, dogs and vehicles. Climate change will compound these stresses. For example, koalas will need to search further afield for palatable leaves, trees with higher leaf moisture and shade. This will not only increase the vulnerability to dogs and vehicles as koalas walk across the ground, but the additional stress is also likely to increase the impact of diseases such as chlamydiosis on the fertility, and ultimately the viability, of the population. Further, fires will increase in both frequency and intensity with climate change (Cary 2002; Hasson *et al.* 2009; Williams *et al.* 2001), and our studies at Port Stephens, in coastal NSW, showed that fires have an immediate impact on the local koala population (Lunney *et al.* 2004, 2007). However, fires reduce habitat quality only briefly, with koalas moving back into the regenerating bush within months, and breeding within a year (Matthews *et al.* 2007). Fire is also less of an issue in Gunnedah's largely agricultural landscape.

The issue of the prevalence of the disease chlamydiosis needs special mention. While definitive evidence of prior presence of this disease amongst koalas from this region is not documented, anecdotal evidence of an experienced local veterinarian (David Amos) suggests that clinical chlamydiosis was historically (over the last 35 years) absent or extremely rare. Smith (1992), in his report of koalas and land use in the Gunnedah Shire, reported that 84% of 108 respondents to a public survey did not consider that disease was a cause of death. However, 14% said that disease was occasionally the cause of death and 2% said it was commonly the cause of death. Whether it was chlamydiosis, or some other disease, was not reported. It is an interesting, but not unexpected finding, that overt clinical chlamydiosis appears to have increased dramatically in prevalence associated with a period of intense climatic and nutritional stress. In a climatically different, but potentially similar population-stress scenario, it has been noted previously that chlamydial disease can result in infertility, contributing to population decline (Handasyde 1986; Martin and Handasyde 1999), with the conclusion that management of koala populations to minimise its impact is crucial. Although previous authors have attributed clinical signs of chlamydial disease to indicate koala populations under stress from habitat disturbance (Weigler *et al.* 1988; Ellis *et al.* 1993; Jackson *et al.* 1999) or concomitant disease (Canfield *et al.* 1991), none had considered the impacts of weather events or climate change. The ultimate expression of clinical disease is the result of a complex interaction between the host, pathogen and environment. Climate change is likely to impact directly on the environment and host dramatically, thereby changing the balance between host and pathogen significantly. In an environment of fractured habitat and peri-urban stressors, this change in balance is likely to play an increasingly important role in population viability and species survival. Although traditionally disease alone has not been regarded as a major driver of extinction (de Castro & Bolker 2005), this view is changing with two recently documented extinctions as the direct result of disease: the land snail *Partula turgida* (Cunningham and Daszak 1998) and the sharp-snouted day frog *Taudactylus acutirostris* (Schloegel *et al.* 2006).

Apart from the prevention of introduction of novel disease agents, management of the environment will become increasingly important and likely the most cost-effective and practical way to mitigate the impact of disease in wildlife populations. There may be a number of practical strategies by which this may be attempted, but revegetation programs that provide benefits in many ways may also be of assistance in this regard. The reasons as to why chlamydial disease has different clinical expression (Canfield 1989; McLean 2003) and impact on different koala populations remain unknown, however the effect appears significant in some populations and likely to increase in significance over the geographic range of the koala in the future. It is becoming more imperative to investigate chlamydial epizootiology thoroughly in different free-ranging koala populations in order to be able to develop effective management strategies to mitigate the additional effect of chlamydiosis on koala population survival. Ultimately, we need to investigate the nature of the interaction between wildlife disease and other threatening processes, with the aim of providing practical strategies to minimise the impact of disease on a wild koala population through appropriate habitat management in the face of climate change.

Drawing the lessons from Gunnedah

The Liverpool Plains are among Australia's prime agricultural landscapes; there are no national parks, and only a scattering of small state forests. The conservation of biodiversity on private land is a goal that many local landholders share, and the koala is a conspicuous example of their recent successes. While we now have a broad understanding of tree selection, patch selection and the movements of koalas between patches at a regional level, leaf physiology at the chemical level, soil status for vegetation and health status of various koala populations, what remains unclear is the inter-relationship of these factors. The challenge for adapting to climate change is to see what drives the patterns of koalas' use of habitat across an agricultural landscape.

One of the advantages of research in Gunnedah is that we are working with the Liverpool Plains Land Management, a community-based natural resource management organisation. Our project's original aim was to look at the success of the environmental plantings in the 1990s for koalas. We are examining that success, and specifically examining the extent to which environmental plantings have propelled that success. Climate change looms as a new threat, and the response will be to undertake further targeted plantings in locations where there is moisture in the ground during droughts. We also need to recognise the lag time between establishing successful plantings and their capacity to be utilised by koalas. This will involve a better understanding of koala movement patterns and how the koalas use the landscape over the long-term, including the time period before koalas include environmental planting within their home ranges. Current data from our work in Gunnedah, and from revegetated mine sites such as on North Stradbroke Island (Woodward *et al.* 2008), indicates that this is about 10 years.

Research is needed to assess which trees koalas select in extreme conditions. Most field research includes surveys for koala dung under trees (also known as scats or pellets). We recognise that the counting of koala dung in a systematic fashion can show which trees are used, but dung counts cannot show which trees were selected in heatwaves or what was the sequence of trees selected, because of the variable rate of decay of koala dung under different conditions (Rhodes *et al.* 2011). We need to know where the koalas move to and what trees they use during the drought, and more specifically during the heatwaves at the peak temperatures in the daytime and the cooler hours at night. Thus, the next steps in the research in the Gunnedah area are to determine the night versus day tree preferences, and tree preferences in the drought. Shade trees are likely to be more important than has been recognised, and feed trees are well known to be critical. Drought has also been identified as an issue for koalas in central western Queensland (Ellis *et al.* 2010) and south western Queensland in the semi-arid regions (Seabrook *et al.* in press).

What we know about the interactions between koalas and their food trees suggests that elevated concentrations of atmospheric CO_2 may threaten some populations of free-ranging koalas. We suggest two conservation approaches: (i) identifying and protecting populations of koalas on fertile sites and (ii) dedicating additional fertile sites as part of the conservation estate and rehabilitating those sites with an appropriate mix of tree species and genotypes. The importance of soil fertility for the sustained conservation of leaf-eating marsupials has long been recognised (Braithwaite *et al.* 1984; Cork and Catling 1996; Braithwaite 2004) and significant effort is being made to conserve these better quality sites. Similarly, recent research has identified some of the causes of selective feeding by koalas, particularly among trees within a single species (Moore *et al.* 2004), and this information can be directly applied to rehabilitating koala habitat.

We are looking at a more general problem than a one-off heatwave in Gunnedah. Consequently, tree selection for plantings will now need to consider how trees are used by koalas for food, water content and resting. This is likely to require different combinations of trees, and these combinations are likely to vary through the range of the koala, and even across Gunnedah. One of the primary lessons from recent studies of habitat selection and the impact of local conditions is that while the list of issues remains the same, the rankings within the list varies sharply according to location (Crowther *et al.* 2009; Rhodes *et al.* 2008; McAlpine *et al.* 2006). This lesson also applies generally to climate change and koala populations. What we derive from Gunnedah will be relevant elsewhere, but more particularly, or at least more quickly, in the western, drier parts of its range.

Koalas cannot avoid extremes of weather, except through localised tree choice. Understanding interactions between koalas and their food is vital because it provides direct input into models that can predict range contractions under various climatic scenarios (Kearney *et al.* 2010). Modelling by Adams-Hosking *et al.* (2011), under realistic projected future climate changes, with the climate becoming increasingly drier and warmer, showed a significant progressive eastward and southward contraction in the koala's bioclimatic envelope in Queensland, New South Wales and Victoria. We agree with Adams-Hosking *et al.* (2011) that a proactive approach to conservation planning is necessary to protect the koala and other species that depend on eucalypt forests.

This case study of a koala population on the prime agricultural landscape of the Liverpool Plains, demonstrates that it is possible to incorporate basic research on koalas, from field studies to laboratory studies, simultaneously with applied strategies to conserve a local population. It also demonstrates the value of participating in the interaction between policy and field science. We argue for retaining that interdisciplinary combination to conserve our native fauna. The end users will extend beyond the Liverpool Plains, via local government and state agencies, to the federal parliament.

The observations we made in December 2009 of desperately dehydrated koalas allowed us to interpret how climate change will directly impact on koala populations. In turn, that interpretation allowed us to integrate the contributions from cross-disciplinary links, e.g. predictions of heatwaves compounding the gradual, but relentless, degradation of leaf quality for koalas as CO_2 levels rise, and the rise of *Chlamydia* and its impact on fertility. It also contributes to our grasp of how to manage for sustainable native fauna populations and threatened species by distinguishing among the multiple causes of population change. This research integrates koala conservation within an adaptation strategy for climate change. In this project, we are now considering how we, as koala managers, can adapt our land and restoration management strategies.

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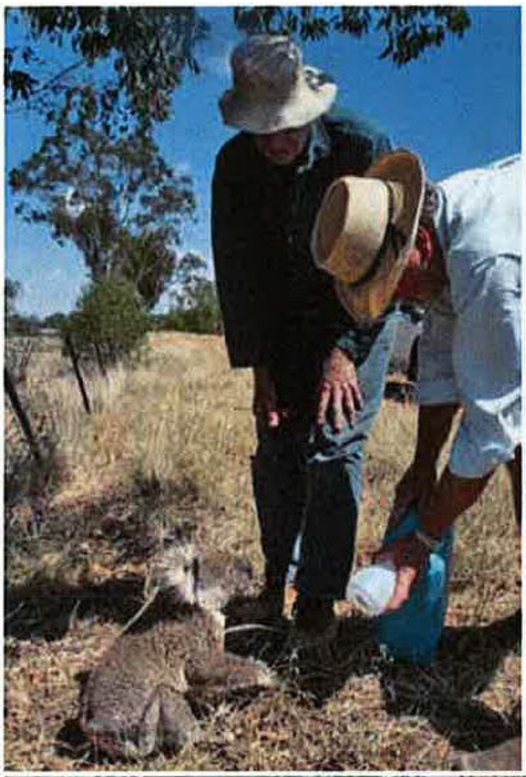
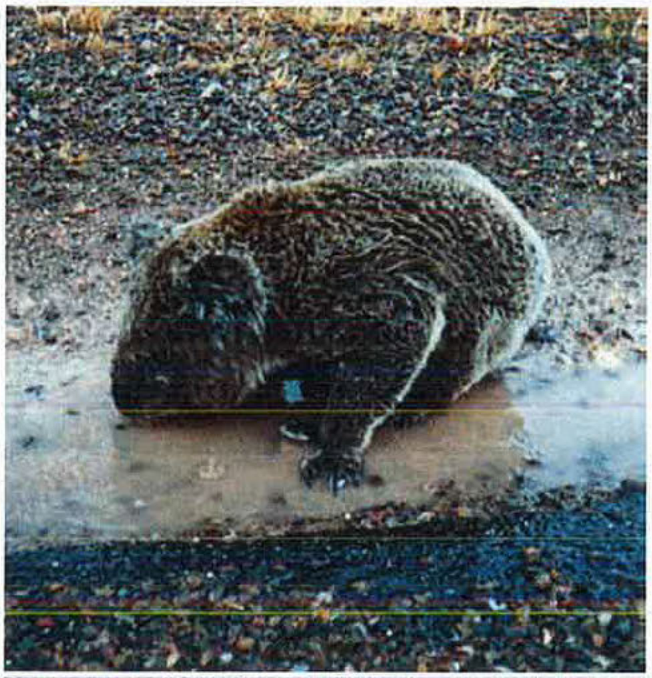
Billboard on the Kamilaroi Highway between Quirindi and Gunnedah featuring John Lemon and his daughter, Jacqui Lemon with the caption: 'Welcome to Gunnedah, Koala Capital of the World'. Photo by Dan Lunney April 2011.

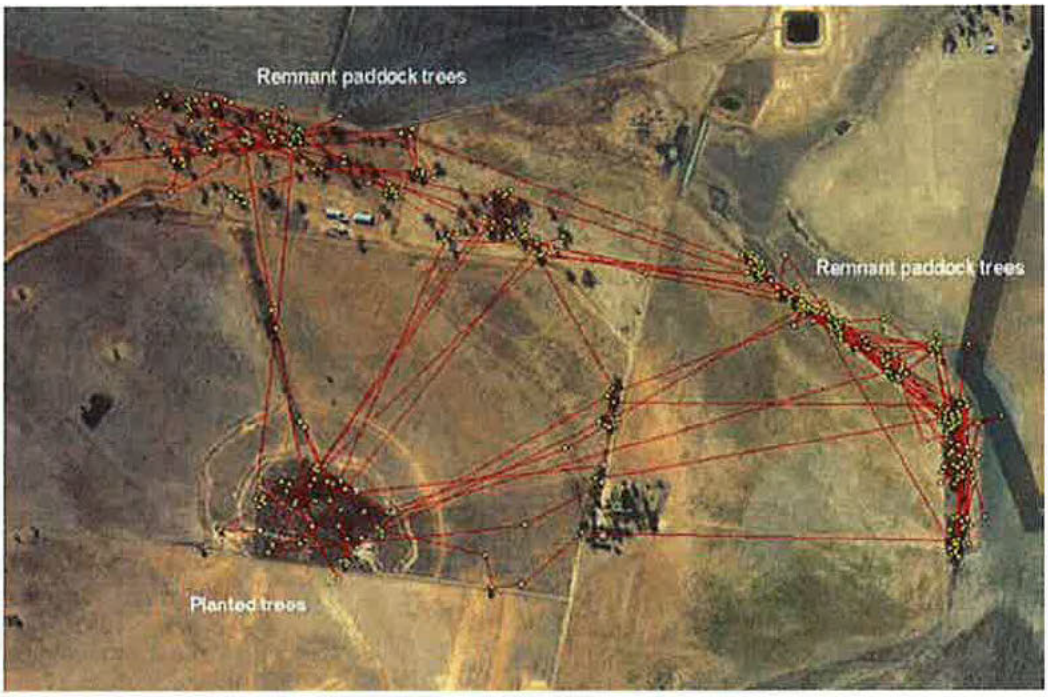


This striking sequence of a koala drinking from a water bottle shows how the intense heat wave of December 2009 during the drought drove the koala to behave in an extraordinary manner. The koala depicted here is a wild koala. John Lemon (with the straw hat) misted the koala with a spray bottle normally used for watering indoor plants. The koala rushed towards John Lemon and drank from the bottle. When he attempted to withdraw the bottle to refill it, the koala embedded its claws in his hand. When John freed himself and refilled the bottle, the desperate koala wriggled through the fence and clasped John Lemon's arm. This extraordinary behaviour illustrates how dehydrated the wild koalas had become during the heat wave period. Note the dry grass showing the state of the drought at the end of 2009. Photograph D. Lunney December 2009. (Note: Rob Wheeler is the person in the cloth hat.)

While we were radio-tracking in December 2009 in Gunnedah, we noticed a koala at the base of its tree. It was so limp that it was lying on the ground. The farmer looking at it said that if it had been one of his stock, he would have shot it to put it out of its misery. We did not want to take that step. We took it to the local veterinarian (David Amos), who treated it with intravenous fluids. This large (ca 8 kg) koala required 2 litres to recover; indicating approximately 25 % dehydration, a condition very close to death. David Amos pointed out that, without the drip, it would have died of dehydration. This was one of four koalas treated in the December 2009 heatwaves. Photo by Dan Lunney December 2009.



In late December 2009, it rained in Gunnedah. A common comment was that koalas were seen drinking in pools at the edge of the road. This was so remarkable that photos were included in the local press. Photos courtesy of Marie Hobson of the Namoi Valley Independent.



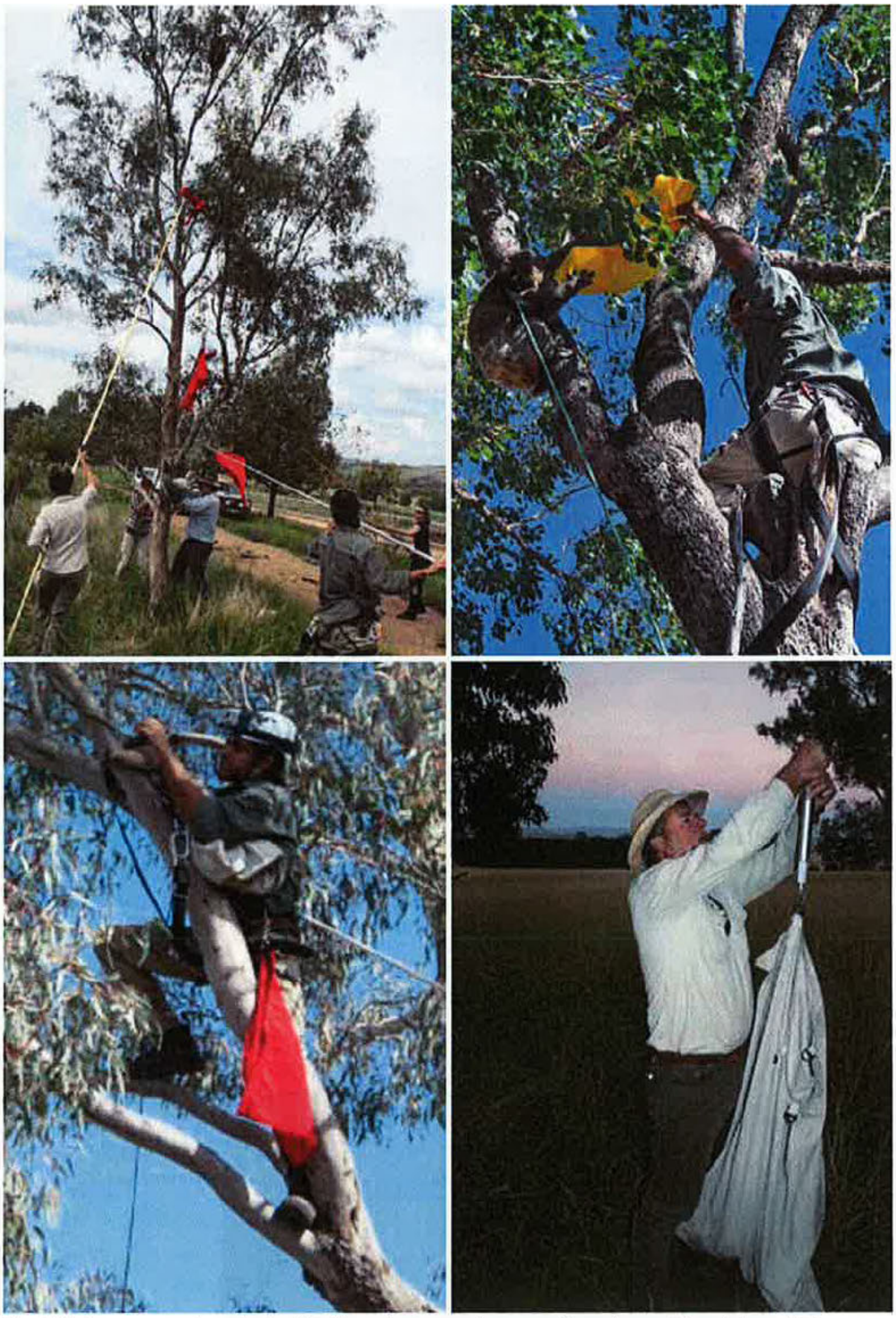
The movement of koalas in Gunnedah from the data downloaded from the GPS units in the collars on the koalas shows that they use young trees, and they will cross an open paddock to reach new trees. Location: "Emerald Plains", Gunnedah.

Koala in a large River Red Gum *Eucalyptus camaldulensis*, a preferred tree species. The next steps in the research in Gunnedah include determining the night-versus-day tree preferences and tree preferences in the drought. Shade trees are likely to be more important than has been recognised, and feed trees are well known to be critical. Photo by Dan Lunney December 2009.

Koala being treated by Gunnedah veterinarian David Amos for dehydration. David Amos commented at the time that koalas would be "dropping like flies" from the heat. Photo by Dan Lunney, December 2009.

A koala hiding in a hollow in a tree on a heatwave day in Gunnedah in November-December 2009. This is an extra ordinary sight, and so rare that it is worth recording. It was found because it was wearing a radio-collar and John Lemon was tracking the koalas to check on their well-being.

Photo, John Lemon, November 2009.



The OEH team capturing a koala. Catching a koala requires a number of expert hands to assist to ensure a speedy and safe operation. The second and third photo show expert tree climber and koala catcher George Madani climbing a tree to catch a koala and the fourth shows John Lemon weighing the koala in a cloth bag. This sequence displays not only the difficulty of seeing a koala at any time of day in such dense foliage, but also that the koala was willing to walk through long grass to reach the desired tree. This sequence of photographs sits in stark contrast to those of December 2009 during a heat wave at the end of a long drought (as seen previously where the koala is drinking from a water bottle). Photographs D. Lunney October 2010 and April 2011, and E. Stalenberg October 2010.

Dan Lunney and John Lemon (in the straw hat) of OEH fitting a captured koala with a GPS tracking collar and then releasing it back into the wild with the collar. The photo on the top right shows the care taken to ensure that each collar was fitted at a comfortable tightness around the koala's neck. Photographs C. Orscheg and D. Lunney October 2010.

The Gunnedah landscape is characterized by large open fields, lines of trees and some clumps of trees as well as occasional paddock trees. In this photograph, a train is carrying a large load of coal to Newcastle. Gunnedah has a history of both mining and agriculture. Photograph D. Lunney April 2010.

Veterinarian Jo Griffith and honours student Melissa Retamales (University of Sydney) conduct a health check of a captured koala, with assistance from John Lemon (OEH) at the Gunnedah Resource Centre. All koalas captured in 2008, 2010 and 2011 were given health checks to investigate population health, breeding status and disease. Photograph D. Lunney April 2011

Clinical chlamydial conjunctivitis in a 4 year old male koala. Photograph Joanna Griffith April 2011

Rump pelage stain and evidence of urine leakage in an aged female koala. Photograph Joanna Griffith April 2011

An Ecological Approach to Koala Conservation in a Mined Landscape

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ABSTRACT

Gunnedah, in north-western New South Wales (NSW), including the town, the surrounding Liverpool Plains and the Pilliga forests to the west, are currently the subject of intense mining interest for coal and coal seam gas. Achieving positive outcomes for koala conservation on mined landscapes will require a sound grasp of koala ecology; and local knowledge of koala movements, tree choice and associated threats to the continued survival of koalas, particularly roadkill from increased mining infrastructure. This requires a research-oriented approach to testing ideas applicable to the long-term survival of koala populations. Our recent koala research in NSW has shown that, in 2006, Gunnedah had the largest koala population west of the Great Dividing Range, and the only population in NSW that was expanding. That prompted us to instigate a detailed study in 2008 - 2011 to determine, *inter alia*, whether the koalas were using trees that were planted in the 1990s to cope with rising soil salinity. Our GPS-tracking has shown that regrowth trees as young as ten years old can attract koalas. In 2009, the demise of about a quarter of the local koala population from an intense heatwave gave us a foretaste of how habitat and climate change interrelate at the landscape scale. We are now examining the optimal combinations of tree choice, and patch size and shape, for habitat restoration. This will be relevant to local coal seam gas and coal mine proposals, and ongoing mitigation actions. The Senate enquiry of September 2011 on the koala and demonstrated the intense public interest in the survival of this iconic species. Its subsequent listing for Queensland and NSW under the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999* further raises its profile and obligations for management of koalas and their habitat. It will take considerable effort to manage the Liverpool Plains koala population for the next 50 years in the face of extensive land-use changes from mining, and the attendant threats from road kill, compounded by the new threat of climate change manifesting itself as an increased frequency of heatwaves and more severe droughts. This paper describes the research that underpins these conclusions, identifies some of the research approaches needed, argues for working strategically now, rather than try to patch up matters after the event, and presents a set of guides for environmental plantings.

INTRODUCTION

Gunnedah, in north-western NSW, including the town, the surrounding Liverpool Plains and the Pilliga forests to the west, are currently the subject of intense mining interest for coal and coal seam gas, both for and against. It is front page material in the local paper, the *Namoi Valley Independent*, and it is an issue on national television. The public debate is certain to escalate as mining proceeds. This paper discusses a significant dimension to the debate – the future of the koala populations of the Liverpool Plains and the Pilliga forests. The communities of Gunnedah and the Liverpool Plains are proud of their koalas. The flags flying in the main street of Gunnedah proclaim it to be the 'Koala Capital of the World'.

There are long-standing koala conservation initiatives being carried out by a wide range of authorities and community groups across the region, and a high level of community awareness of koalas and the issues that they confront. To the extent that mining will impact on the success of these initiatives, there is certain to be strong community resolve to protect koalas from the growing list of threats that they face both locally and across the region.

To ensure that the flags keep flying will require well-informed ecological responses. It is essential to understand where the koalas occur around Gunnedah, what threats they face, what management actions have benefitted the local

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koalas, and how the community can contribute to sustaining the koala population of Gunnedah Shire and the Liverpool Plains. Conceptually, this responsibility reaches across the landscape and encompasses the obligations of large groups and entities, such as farmers and miners, local councils, the Catchment Management Authorities (CMAs) and State Government departments. In 2011, the Senate conducted an enquiry into the national status of koalas (Commonwealth of Australia 2011) which resulted in a great deal of publicity and controversy surrounding koalas throughout the country, and now that the koala is listed federally as a threatened species then the Commonwealth Government will also become an active participant in land use decisions and rehabilitation. This will add to the NSW Government's interest in koala conservation where the koala has been listed as a threatened species under NSW legislation since 1992 and is currently subject to a NSW koala recovery plan (DECC, 2008).

This paper is also directed to individual actions, including property management, the care of sick and injured koalas, and participation in surveys of koala presence. This approach is based on the recognition that koalas are mobile animals that are dependent on an optimum set of tree species in which to feed or take shelter, and koalas will traverse open paddocks and cross busy roads to reach the trees that they depend upon (DECC, 2008; Commonwealth of Australia, 2009; Crowther *et al*, 2009; Lunney *et al*, 2012). This approach goes beyond habitat conservation and rehabilitation on specific properties to take into account the dynamics of a population of koalas and all its needs. Habitat conservation and restoration is essential, but it is not enough. If we are to maintain a population of koalas in Gunnedah and across the Liverpool Plains, and indeed, the entire Namoi CMA, particularly the Pilliga forests to the west of Gunnedah, then we need a dynamic, landscape-scale approach. Such an approach is possible, and this paper outlines some of the major steps required, based upon recent local koala research, particularly our 2008 - 2011 study of the restoration of koala habitat in Gunnedah. The paper is a guide to managing a regional koala population in a landscape about to be transformed by coal and coal seam gas mining. It is preferable, in our view, to write such a paper now, even though our work is still underway, rather than wring our hands in ten years and lament that we did not speak about this crucial and emerging subject.

The foundation of this paper is a research project recently conducted by the team from the Office of Environment and Heritage (OEH) (2008 - 2011), under a NSW Environmental Trust Grant won by the Liverpool Plains Land Management (LPLM) in 2008, entitled: '*Restoring Koala Habitat in Gunnedah: Building on a 1990 Success*' (Lunney *et al*, 2012). Not only did this project demonstrate the value for koalas of the trees planted for soil conservation and habitat purposes in the 1990s, but it also foreshadowed two emerging problems for koalas (Lunney *et al*, 2012). These are the impact of heatwaves and drought, and the issue of the koala disease Chlamydia, including its impact on breeding success of koalas. An additional threat is that of the coal mining industry reducing koala habitat, fragmenting what remains, and increasing the risk of koala deaths from vehicles as mine infrastructure increases. These provide a timely warning of the potential for combined impacts from predicted climate change and other threats for wildlife in the region. Thus, while tree planting and restoration has benefitted the koala population, its future is not assured unless these new issues are understood so that future restoration can be approached strategically. Strategic restoration would be more focused on which tree species to plant, and in what soil types, and would determine which planting patterns will provide the most benefit for koalas in the hard times, such as heatwaves and droughts, in a landscape modified by intensifying land uses. It is also necessary to incorporate other species, ie integrated plantings that benefit a wide range of native fauna, not just koalas.

The next step following from the research so far is to study the Gunnedah koala population over an even longer time frame than the 20 years in the OEH study of 2008 - 2011. That study examined the success of the 1990s plantings and found that koalas use trees as young as ten years old, and that plantings will contribute to koala conservation in a relatively short period of time. A more comprehensive project would extend back to first settlement in the region, from the time of explorer John Oxley in 1819 to the present to arrive at recommendations to manage the landscape and koala populations into the future, until at least the changes brought about by coal mining have stabilised at a point where there is a good assurance of a long-term future for the koala population across the Liverpool Plains and the Pilliga. The scientific underpinning for such a future must be ecological, with a crucial social component that involves the community. It must also have the practical component of working with existing legal requirements, relevant authorities and the land owners to maximise the benefits for all parties, while still holding to the view that the flags in Gunnedah should be maintained between generations of Gunnedah residents and visitors to the town.

There are two new players on the scene in 2012 – the Commonwealth Government and the coal and coal seam gas mining industries. On 30 April 2012, the Commonwealth Government listed the koala as vulnerable in NSW and Queensland, under the *Environment Protection and Biodiversity Conservation Act 1999*, thereby formally involving the Commonwealth in major decisions affecting the survival of koala populations, which will include major mining industries. The coal mining industry, including coal seam gas, is about to transform the landscape of the Liverpool Plains, and elsewhere in the Namoi CMA region, particularly the Pilliga forests, which are, or were, the centre of a major koala population in north-western NSW. Available information points to a drastic decline in the Pilliga population in the last 15 years. Along with the koala population on the Liverpool Plains, the Pilliga koala population made up the major component of the inland koala population of NSW and made the Namoi CMA region a critical area for inland koalas in NSW (Crowther *et al*, 2009; Lunney *et al*, 2009). The spotlight is now being thrown on these koala populations and their future. Mining and koala survival are thus linked. The approach we advocate is to take a regional landscape approach to population management. This will involve not only habitat mapping, preservation and replanting, but also detailed demographic studies so that present and future populations of koalas survive. We point to this critical feature because habitat mapping, preservation and planting give no assurance that a koala population will endure. Although the rapid assessment techniques of identifying koala habitat by koala pellets (droppings or dung) under trees can cover a large area quickly, they cannot assess the trends in koala numbers and the causes of the changes, other than patterns of habitat change. If coal mining and koalas are to co-exist, then a robust strategy for koala conservation is essential. That strategy will need to take in all elements in koala population biology, not just habitat identification and management. We now take a step back to say how we arrived at these conclusions, then proceed to make a series of recommendations so that others can see the steps and comment on our proposals.

THE LIVERPOOL PLAINS LAND MANAGEMENT/ OFFICE OF ENVIRONMENT AND HERITAGE STUDY OF KOALA HABITAT RESTORATION 2008 - 2011

Context and aims

In a major NSW state-wide koala survey in 2006, Gunnedah and the Liverpool Plains were identified as a rare bright spot in NSW because the koala population was expanding, against the state-wide trend (Lunney *et al*, 2009). The environmental plantings under the 'Bearcare' program in the 1990s, planted by landholders as part of a landscape project to combat soil salinity, improve biodiversity benefits and reduce soil erosion, may have contributed to this result, and it had always been intended that there would be follow-up research of koalas' use of these plantings.

A subsequent investigation (Crowther *et al*, 2009) showed that, although the four CMAs in the north-eastern part of NSW carried the same list of issues facing koalas, each CMA had a different ranking for the various threats. This pointed to the need for local solutions within each CMA, and even within parts of each CMA, indicating that there is no simple formula to managing koala populations. These findings led to a detailed project on the Liverpool Plains where we worked property by property, koala by koala, and tree by tree. This project involved radio-tracking koalas throughout Gunnedah and the Liverpool Plains to investigate their use of different habitats and how and when they moved across the land.

The primary aim of the project was to investigate koala movements to determine tree choice, with particular reference to their use of the environmental plantings (see Appendix 1). However, a critically important additional element was brought into the study while it was under way. Extreme weather - heatwaves in late 2009, near the end of a long drought, introduced a major climate change element. The opportunity was taken to examine the impacts of these events on local koalas in relation to deaths of koalas during the heatwaves, reduced breeding rate, and the disease Chlamydiosis becoming visibly manifest in the local koala population (Lunney *et al*, 2012).

Methods

The koala is a cryptic species and can be difficult to observe directly in the field. The standard methods employed to survey koala habitat have relied on surveys of koala dung (ie pellets, or scats) under trees. While this is a simple and easy means to detect koala presence and tree use, it does not provide information on the reasons why koalas use particular trees, or information on how often koalas move across the landscape and in what weather conditions. Koalas will mostly move at night and spotlighting or continuously following individual animals using radio-tracking collars can track these movements. The number of 'fixes' or sightings during a spotlighting survey are limited as the method relies on the koalas facing the spotlight, or on observers being able to visually discern their fuzzy grey outline. Continuous radio-tracking surveys overcome this limitation as koalas are tracked detecting the radio frequency emitted by a transmitter attached to the animal, however, these studies require considerable time and resources for little reward as only one or two koalas can be continuously tracked by each researcher at any one time. In addition, there are safety issues and other difficulties of radio-tracking at night, consequently radio-tracking is almost entirely limited to daytime, and therefore to trees selected for daytime shelter, not necessarily for food.

We used global positioning system (GPS) tracking of koalas using custom-made (Sirtrack®, Hawkes Bay, New Zealand) tracking collars to assess the use of the landscape by koalas at a local scale. Over the three years of the project (2008 - 2011), we fitted 51 koalas with tracking collars that included state-of-the-art GPS units to record the location of each koala every four hours, including through the night. The collars were therefore designed to collect vastly more night data concerning koala movements than researchers would be capable of in the field. Furthermore, many koalas were tracked simultaneously. The collars were also fitted with an in-built radio transmitter which enabled the research team to periodically check the koalas to gauge their condition and to locate them at the end of study period (maximum six months per koala) to remove the collars. At this point, the GPS data were downloaded. Detailed health checks were also conducted on the animals captured in 2008, 2010 and 2011.

Results

The GPS collars were extremely successful and provided accurate, reliable and continuous data on koala movements throughout the tracking period. The data were insightful in demonstrating that koalas actively use the trees that were planted by landholders in the 1990s. They show that koalas are moving considerable distances across the landscape, with movement of three to four kilometres over several weeks being a common occurrence. This includes movements to and from landholder-initiated tree plantings, between plantings, and between old paddock trees and trees along fence lines and remnant tree patches (Figure 1). Koalas therefore capitalise on the success of the plantings by using the full diversity of habitat resources available.

The data show that koalas are not walking randomly across the landscape, but along the edges of paddocks, roadsides, railway tracks and travelling stock routes (TSRs). The use of isolated paddock trees has been a striking finding and shows that koalas are frequently walking across open paddocks. The level of use of roadside reserves and railway track corridors by koalas highlighted by this study is a major concern, as road-related injury is one of the highest causes of koala death or entry into care.

Detailed information on the trees koalas visited was obtained by locating the animals two to three times during the tracking period. A sample of trees used by koalas on, respectively, Gunnedah Research Centre (Table 1) and Emerald Plains, was measured for species, size and other structural characteristics. Most frequently used species in this dataset are the red gums (*Eucalyptus camaldulensis, E blakelyi*), an ironbark (*E sideroxylon*), and the cypress pine (*Callitris glaucophylla*). The larger Casuarinas on the lawn at Gunnedah Research Centre were frequently used, while the smaller *C cristata* in the plantings had no scats. None of the kurrajongs (*Brachychiton populneus*) had scats present, but they were mostly smaller trees. Overall, close to half the sampled trees were used by koalas at some stage. Koalas were found regularly in non-eucalypt trees such as white cypress pine and wilga (*Geijera parviflora*), possibly because these trees provide considerable shade and protection against weather extremes.

Discussion

Over the three years of study (2008 - 2011), we collected detailed data on the koalas' movements and showed that they move frequently from ten to 20-year old tree plantings, through paddocks, to isolated older trees and to remnant woodland stands. Koalas were frequently found to have walked distances of several kilometres and used plantings

FIG 1 - Close-up of an air photo of the movement patterns of one koala on one property (Emerald Plains) showing the locations (yellow dots) determined every four hours from the GPS data from the collar on the koala, and the yellow lines show the dots joined sequentially. The green patches are scattered regrowth and old trees near the farm sheds.

TABLE 1

Percentage of trees sampled on Gunnedah Research Centre with koala scats present.

Species	Number with scats present	Total no of trees examined	Use rate (% of trees of that species with scats present)
Eucalyptus camaldulensis	21	26	81%
Callitris glaucophylla	19	24	79%
Eucalyptus sideroxylon	12	17	71%
Casuarina sp sample 5 – large trees on lawn	11	17	65%
Eucalyptus blakelyi	10	16	63%
Eucalyptus mellidora	15	25	60%
Eucalyptus albens	11	19	58%
Eucalyptus populnea subsp. bimbil	15	31	48%
Angophora floribunda	5	17	29%
Acacia pendula	2	14	14%
Acacia salicina	1	8	13%
Brachychiton populneus	0	25	0%
Casuarina cristata	0	17	0%
Total numbers of trees sampled	122	256	48%

along fence-lines, train tracks and roadsides. This shows how far koalas move regularly to gain access to preferred trees and locations, but this movement renders them vulnerable to collisions with cars and trains. Importantly, it also shows that koalas are amenable to using tree plantings such as those originally planted by landholders in the 1990s as part of projects to combat soil salinity, improve biodiversity benefits and reduce soil erosion. Koalas capitalised on the success of the plantings by using the full diversity of habitat resources available. This is a significant finding because until now the view that young trees, or saplings, could provide valuable koala habitat had yet to be confirmed. This study confirms the value, even in the short term, of planting feed and shade trees to contribute to sustaining Gunnedah's koala population and allowing the koala population to increase, and helping to mitigate the impacts of habitat loss and fragmentation across the rural landscape.

This restoration study made a number of fascinating findings and raised new questions, and it consequently received wide exposure in the local, state and even national media (Lunney *et al*, 2012). We maintained continuous working relations with the landholders in the area, particularly the owners of Dimberoy, Turon Park, Emerald Plains and Pine Cliff, as well as the Crown land at the Gunnedah Resource Centre. We also received considerable support from a local veterinarian (David Amos). We have discussed the need for an appraisal of long-term changes in koalas on the Liverpool Plains with the Gunnedah Historical Society, but that follow-up study is yet to commence. Gunnedah Shire Council and the Namoi Catchment Management Authority have indicated that they will draw on the recommendations from the study to help with their management and planning responsibilities. Currently, Gunnedah Shire Council is developing a Comprehensive Koala Plan of Management, which will materially assist council and the community to conserve koala habitat, habitat being the central focus of such plans under NSW planning legislation. The continued interest and support shown by these local organisations, land owners, local media and the broader community was one of the most rewarding aspects of the project.

Capitalising on the success of the 1990s plantings

We have produced, or are still working on, a number of public, scientific and policy papers, conference presentations and posters, public talks, media releases and numerous feature articles from this project. This paper, including the recommendations and supplementary material attached, are intended to assist managers of public and private lands, particularly lands to be mined, in the management and restoration of koala habitat, while reducing the vulnerability of koalas to existing and future threats.

We are currently planning the next stage in the project, for which funding is yet to be found. This research will comprise a collaborative study, including OEH, University of Sydney, industry and local agencies, to examine the new issues raised from this study so far, namely, climate change and disease, coal and coal seam gas mining and the capacity of the Gunnedah koalas to adapt to these new and ever-increasing threats.

The project findings have led us to develop recommendations for future plantings and landscape management. The koala movements are being modelled against land use and vegetation cover to further refine the recommendations and to draw inferences regarding the importance of planting size, shape, and tree species composition, and in relation to other features in the landscape such as proximity to water bodies, remnant woodland patches and roads.

New questions

Climate change and disease

In addition to meeting our original aims of establishing the value of the 1990s plantings, our study has uncovered a number of previously unforeseen, but increasingly important, issues that the koala population, and indeed other wildlife species inhabiting the region, will need to face in the future. We refer to the novel, but pervasive threat of increasing extreme weather events as a consequence of climate change, which is a recognised key threatening process (Lunney and Hutchings, 2012), in conjunction with other threats, including disease. These issues identify the need for a next phase of the study: to examine the capacity of the Gunnedah koalas, and land managers, to adapt to the long term with new and rising threats.

Heatwaves in November and December 2009 occurred just before the end of an intense, prolonged drought. The heatwaves lasted around 15 days and during this time, two of the collared koalas were taken into veterinary care to be revived through rehydration and then re-released. Two additional tracked animals succumbed to the heat in the field. Koalas were observed displaying extraordinary behaviour to overcome dehydration in the intense heat (Figure 2 shows a dehydrated koala drinking from a bottle during the heatwave), and a number of deaths of wild koalas were recorded by landowners, the local veterinarian and members of the public. After scaling up our observations of the collared koalas and taking into account evidence from interested landholders, we estimate that about 25 per cent of koalas died locally.

FIG 2 - John Lemon offering a drink to a dehydrated wild koala. The koala left the place of the tree where it was sheltering to take the water. Photo by Dan Lunney, December 2009.

Over the course of the project, the region also experienced a major flood. The impact of floods on koalas is yet to be determined, and no previous studies have been conducted on the impact of floods on koalas from which to draw comparison. However, it is unlikely that the floods would have benefitted the koalas. On the contrary, the floods almost certainly restricted movements, limited feeding opportunities, and may have weakened the koalas thereby rendering them more vulnerable to disease and predation. These examples foreshadow the potential impact of climate change on koalas as the severity and frequency of natural disasters and extreme weather events increases as predicted. The study also highlights the role of land managers in helping safeguard koalas against these events, such as by providing trees that give shade and maintaining free water to prevent koalas becoming dehydrated during a heatwave.

Health checks of each koala captured were conducted over the course of the study. Koalas were captured and collared for three consecutive years in spring and two consecutive years in autumn. This allowed for an analysis of the trends in breeding success for the population. The percentage of females with young declined between October 2009 and October 2010. In 2010, the health of the population appeared to have also declined, and this enables us to predict that the number of young leaving the pouch would decrease even further (Lunney *et al*, 2012) Pathology testing in 2009 of local animals captured for this project confirmed the presence of Chlamydia, a sexually transmitted infection which has been known to cause infertility in koalas (M Krockenberger and J Griffith, University of Sydney, see also Lunney *et al* (2012) for more details). Mounting evidence suggests that the incidence of infection is increasing in the population. This area had previously been considered to be free of chlamydia because there had been no overt signs of the disease. The decline in health of the population and the decrease in numbers of females with young are likely to be the cumulative effect of the heatwave and the increase in chlamydial infection throughout the population. These examples foreshadow the potential impact of extreme climatic events, such as heatwaves and droughts, on the region's koalas which, in conjunction with other threats such as habitat loss and degradation through development (especially on the scale anticipated as a consequence of mining), predation by dogs, and deaths on the roads (especially with more mining traffic) and railway lines that pass through koala habitat, have the potential to cause catastrophic population decline.

Mining

To a large extent, mining on the Liverpool Plains and the Pilliga forests is a relatively new threat to koalas in the region. Most of the mining activity is in the form of proposals but we now know enough about koala ecology and the local area to give a reasonably accurate forecast of the impact of coal mining and coal seam gas extraction on the koala populations in these two vital locations. The threats from mining fall into three categories: loss of habitat and fragmentation of what remains; additional mortality threats from increased vehicle and train traffic; and bushfires in the Pilliga. What the heatwave of 2009 demonstrated is that a population of koalas under stress can show an increase in the debilitating disease chlamydia, with reduced fertility as a result (Lunney *et al*, 2012). Without knowing the exact extent of future coal mining proposals, the apparent scale of the operation is sufficient for us to conclude that these important regional populations will be threatened by mining. The population of koalas in the Pilliga was estimated to be about 15 000, 15 years ago (Kavanagh and Barrott, 2001) but researchers familiar with the area and its koalas, including Rod Kavanagh and also OEH ecologist Harry Parnaby, have observed that the koalas now appear to be rare in the Pilliga (Kavanagh and Parnaby, 2012). That loss can be largely attributed to an extended drought and the extensive fires of 2006. Therefore we cannot rely on the Pilliga koala population to recolonise a depleted koala population of the Liverpool Plains if that were to occur. A more important conclusion is that a large, apparently robust population of koalas, such as in the Pilliga forests, can collapse. With this knowledge, and given that mining has not yet begun is major expansion phase, now is the time to take a strategic approach to managing the koala populations of Liverpool Plains and the Pilliga forests. By strategic, we mean knowing how the population moves across a large area irrespective of property boundaries. It is our view that the populations of koalas on Liverpool Plains and the Pilliga Forests need managing, and their long-term survival will depend upon how we manage the land as it is being used, such as through mining, how it is rehabilitated and on what timetable; at least decades and presumably up to a century.

APPLICATION OF RESULTS

The study in Gunnedah, on which we are basing our current conclusions and recommendations, commenced prior to the release of the 2008 NSW Koala Recovery Plan and National Koala Conservation and Management Strategy 2009 - 2014 (DECC 2008; Commonwealth of Australia 2009). The Recovery Plan states that Gunnedah is one of the specified priority locations for study, so the results for our study will feed back into the NSW recovery process for koalas. This highlights that the findings have application at state and national levels by building greater understanding of the koala's ecology and therefore contributing to its conservation.

This project is primarily intended to feed into the shire-wide management of koalas across all land tenures in Gunnedah. For Gunnedah to maintain its claim to be the 'Koala Capital of the World', it will need to have a koala management plan that dovetails with the 2008 NSW Koala Recovery Plan and the National Koala Conservation and Management Strategy 2009 - 2014, and have its own Comprehensive Koala Plan of Management under State Environmental Planning Policy 44. This plan is currently being prepared, and our research will assist in its implementation.

To the extent that mining proceeds across the Liverpool Plains and alters the landscape, there will need to be a major undertaking to conserve, remediate or replace koala habitat affected by mining. The scale of the mining foreshadowed is of considerable international proportions and we can predict that mining and associated infrastructure (eg pipelines, roads, railway lines) will remove koala habitat, cause fragmentation, create physical barriers to movement and increase the threats of cars and trains, and possibly dogs, with an increasing mining-related population on what are now rural lands. On the positive side, we can advise that strategic and well-planned plantings of the appropriate tree species will help to restore koala habitat, remediate disturbed lands and provide additional koala habitat within the time frame of ten to 20 years from planting, provided the plantings are well planned and protected from stock during the establishment stage. A nursery for local trees would be beneficial, but a nursery for koalas while mining is underway, as suggested in one newspaper article, does not make ecological sense.

Recommendations for planting and land restoration on the Liverpool Plains

Based on our research to date on koalas' selection of trees and threats to koalas, we have produced the following recommendations for tree planting programs.

- Tree species: planting tree species of local provenance to provide appropriate food and shade habitat for koalas. Feed-tree species that should be planted include particularly: River Red Gum (*E camaldulensis*), Poplar box (*E populnea*), Yellow Box (*E melliodora*), Pilliga Grey Box (*E pilligaensis*), Blakely's Red gum (*E blakelyi*), and White Box (*E albens*). Shade tree species include Belah (*Casurina cristata*), Kurrajong (*Brachychiton populneus*), Wilga (*Geijera parviflora*) and White Cypress Pine (*Callitris glaucophylla*). Tree preferences for one of the locations is shown in Table 1 and it is noted that not all locations across the Liverpool Plains contain all of the species of trees.

  Planting a mix of these species within one planting can further encourage koalas by providing a range of food and shelter choices, particularly important during times of extreme weather conditions. It is also imperative to avoid monocultures of trees, that would constitute what is known as a perverse outcome (Steffen *et al*, 2009). It is essential that the plantings are well watered and protected from stock in order to become established and grow successfully.

- Connectivity: consideration should be given to the location of new tree plantings in relation to existing woodland remnants, other plantings and to sources of water. New environmental plantings need to be close to remnants and other plantings and direct linkages should minimise the need for koalas to cross open paddocks, roads, and across backyards where they will be vulnerable to vehicles and dog attack. Planting trees along creek-lines and near sources of permanent water will result in trees with higher leaf-moisture and denser foliage for shade, thereby creating valuable koala habitat during droughts and heat waves.
- Road side plantings: the tracked koalas were frequently found moving along road-side and train-line plantings. Trees along road reserves can increase the risk of mortality due to vehicles, as they encourage koalas to spend more time near roads to feed, shelter and to use the linear plantings as corridors to other areas of habitat. To reduce this threat, trees should not be planted next to roads.
- Risk of dog attack: wild and domestic dogs are a significant cause of koala death and mortality, particularly near urban areas and within townships. Landholders should be aware of the risk to koalas from farm dogs and, if necessary, should not plant trees near house paddocks where koalas may be at higher risk from attack.

PLANS FOR FUTURE RESEARCH

The study has uncovered new, but important questions about the potential for the Gunnedah koala population to adapt to the novel impacts of climate change and disease. Our proposed next stage of the project is to focus on the 'tree stage.' This will involve detailed collection of specific characteristics of trees used by koalas including species and structural attributes, and the features of the landscape the koalas visited at different times, seasons and importantly, during extreme weather events. We are currently applying for further funding to undertake a more in-depth and longer-term study to investigate the new questions raised in this project. This research would comprise a collaborative study with university scientists, industry, local agencies and the community to examine impacts of climate change and disease on the population, and to further explore how managers can capitalise on the success of the 1990s tree plantings in order to reduce vulnerability to these threats. In addition, the Pilliga koala population would need to be considered in conjunction with that of the Liverpool Plains in the long-run as forming part of a metapopulation of koalas in the Namoi CMA. They have been historically viewed as discrete but if both are subject of climate change and mining simultaneously and one population is ultimately the source of recruits for the other, then they need to be considered together.

Historical enquiry

When the major survey for koalas in Gunnedah was undertaken in 1990, it was recognised then that the large population in Gunnedah was a phenomenon of the previous ten to 15 years. The immediate question is: where were the koalas between the time that Oxley walked into the area in 1819 and 1990 when the koala population was burgeoning? The reason this question is so important is that the local experts, such as the local veterinarian David Amos and the koala carer Nancy Small, note that they rarely saw koalas in the late 1970s. It was not till the 1980s that koalas started to become common. One implication from this circumstance is that the koala population could dip down to rarity without us having grasped what it is that drives the longer-term changes – the decade by decade changes. The approach taken would be that of historical ecology, an area that the authors have been working on for a quarter of a century, including having established a network of environmental historians to assist in these enquiries.

Adaptation strategies for climate change and mining

We have demonstrated that the 1990s tree plantings were important for providing additional habitat for koalas, but in our research we have uncovered additional issues which are generic for all koalas, namely extreme weather and disease. It is arguable that these threats will overwhelm the positive impact of the plantings in increasing the local koala population, but without the plantings, the impact of extreme weather and disease may have been much worse for the local koala populations. The current threats to koalas will be exacerbated by the loss of habitat from mining, so while rehabilitation will be required to sustain the koala population, before rehabilitation can take place, or reach its threshold for being useful for koalas, there needs to be a management strategy that sustains the koala populations through the bottlenecks that will be created by mining. To underpin the approach to managing the koala population through both a changing climate and intensifying land use, we envisage a research project comprising three components.

We firstly want to study koalas' habitat selection in a changing climate, by measuring the structural and compositional characteristics of trees, patches and landscapes that koalas select during different climatic conditions. We would measure, among other attributes: vegetation type, density, species composition, patch size and the availability of water. Secondly we want to study the links between soils, leaf nutrition and habitat selection by koalas, by assessing leaf nutritional status of the trees that koalas select during different climate conditions, and the soils on which they grow. Thirdly we want to track, on a landscape scale, the epidemiology of the Chlamydia disease throughout the Gunnedah koala population and determine the potential impact of the disease on the population in the context of climate change, the restoration of the landscape and the links among the various rural properties and town.

This project would contribute to the development of a more effective restoration program and koala management plan. This will deliver a long-term benefit in providing quality habitat to ensure koalas are able to adapt to a changing climate and a mined landscape.

The Pilliga forests

The Pilliga forests, 100 km to the west of Gunnedah, are the largest inland remnant of box-ironbark mixed-eucalypt forest in Australia. During the 1990s and until 2005, this forest was regarded as holding the best population of koalas in NSW, with estimates of up to 15 000 koalas (Kavanagh and Barrott, 2001). By any standards, this is, or was, a large population. From recent observations, experienced Pilliga researchers now consider the koala to be extremely rare in this forest. The cause of this decline is potentially of great significance for the koalas of the Liverpool Plains and the remainder of the Namoi CMA. A project outline of current survey and historical investigation has been prepared and could be implemented should funding be available.

CONCLUDING COMMENTS

The koala is a threatened species in NSW, and a Species Recovery Plan was officially launched in 2008 (DECC, 2008). The koala is now listed as a threatened species under Commonwealth legislation, but it is of such iconic importance that there is a National Koala Conservation and Management Plan 2009-2014. In addition, the 2011 Senate enquiry on the health and status of the koala in Australia made it clear that there is widespread concern about the future of koalas in Australia, and great public interest in the matter. Since the proposed coal mining and coal seam gas mining on the Liverpool Plains and the Pilliga forests poses a major threat to the two best clusters of koala populations in NSW west of the Great Dividing Range, it is crucially important to maintain these population, and not allow them to fade as mining proceeds. In NSW, there is a planning instrument – State Environmental Planning Policy No 44 Koala Habitat Protection (SEPP 44) – which provides a formal planning mechanism for local government to conserve koala habitat. Gunnedah Shire Council has recently committed to prepare a Comprehensive Koala Plan of Management for Gunnedah under SEPP 44, which will provide planners with options to address existing and foreshadowed threats, particularly threats to koala habitat. However, while koala habitat is a critical element in conserving koala populations, it is not sufficient on its own. To guide management decisions will require a sustained scientific study, which we characterise as comprising: field-based sampling of koala movement patterns, tree and habitat selection, koala health, population (principally distribution) and causes of change in the population; data interpretation and analysis including landscape mapping and modelling; and write-up for publication in scientific journals and for policy specialists and general readership.

It is also our view that these issues need to be made a matter of widespread public knowledge. Scientists, planners and land managers who have specific requirements comprise only a small proportion of the people interested in the long-term future of koalas in Gunnedah. A distinct component of any major koala study needs to promote education and awareness of the findings. Part of that objective would be to show how community participation can contribute substantially to conserving koalas on private lands, both urban and rural, and on public lands including TSRs, road edges, railway and telecommunication easements, reserves, and corridors of trees planted specifically as community exercises in maintaining biodiversity across a large rural landscape. Many local people have a profound concern about the koalas in their community.

The koala is such an iconic species that people often refer to 'their' koalas, with the implication that there are many target groups for this project, ranging from the town of Gunnedah and the rural landowners of the Liverpool Plains to the entire Australian population, who are concerned about the health, status and sustainability of Australia's koalas. Accordingly, this initiative will strike a chord with groups all the way from Connadilly Street in Gunnedah to Commonwealth Avenue in Canberra. We have identified some specific target groups, at each level of government:

- *Local*: community groups include the Shenhua Koala Community Reference Group, the Koala Reference Group and councillors in Gunnedah Shire Council, Namoi CMA, local Landcare groups, rural landholders and members of the LPLM. The OEH team has worked with Namoi CMA on a koala project in 2006 - 2007 and with LPLM in 2008 to 2011. In addition, both LPLM and OEH have given stories to the local newspaper, the *Namoi Valley Independent*, thereby demonstrating openness to communicating findings and being open to comment.
- *State*: the target groups interested in this matter at a state level will include those groups concerned with the effectiveness of the 2008 NSW Koala Recovery Plan, Landcare groups, farming groups, mining interests, and land-use planners. Most of these groups have local interests in a number of sites while holding the state picture in mind, because that is where many of the decisions relating to landuse and wildlife management are made. The target groups also include the Office of Environment and Heritage NSW, which has land use and wildlife management responsibilities.

  (Note: our OEH team is a part of a State government agency with responsibilities for managing fauna and threatened species, such as the koala. This team was part of the 1990 study of Koalas and Landuse in Gunnedah Shire (locally known as Bearcare; Smith, 1992). This team also conducted a state-wide community survey in 2006 which found that the Gunnedah koala population was expanding, in contrast to the state trend of declining local koala populations (Lunney *et al*, 2009). Determining the reasons why the Gunnedah population should be expanding led to the recent joint study with the LPLM. This study found that the plantings had benefited Gunnedah's koalas; however the study also found that new threats, particularly those associated with climate change, may jeopardise the sustainability of the koalas on the Liverpool Plains in the long-term. Further, if habitat loss and fragmentation were to increase as a result of mining and associated infrastructure, along with losses from vehicles, then this would represent a new dimension to the issue of sustainability of the local koala population.
- *National*: there is an immediate interest by the Federal Parliament in the sustainability of koala populations nationally, as evidenced by the 2011 Senate enquiry into koalas. The Senate Committee's findings included specific recommendations for concerted action from all levels of government, and that private landowners, private individuals and companies will also need to contribute to the collective effort to conserve Australia's koalas. The reason that there will be emphasis on private effort is because most koalas, at least in NSW, occur on private land, particularly the richer agricultural lands that support the specific trees, those with leaves with higher nutrient levels, that koalas are dependent upon.

The Commonwealth Government was already well aware of the impending problems for the koalas by the mid-1980s when it helped fund a national survey of the koala, where each state ran its section of the program. The OEH team on this paper conducted the NSW koala survey in 1986-2007. By 1996, the Commonwealth Government had recognised the need for a national koala conservation strategy, which was formally adopted in 1998, updated by the 2009 - 2014 National Koala Conservation and Management Strategy. These strategies, having been publicly negotiated, have served as a working guide for all levels of government. This provides consistency, and has encouraged networking amongst koala researchers and wildlife managers. The OEH team is a member of the national Koala Research Network, a network of scientists from a range of universities, government agencies and other organisations. The limitation of a national approach is that it may miss the particular combination of threats and opportunities in any one locality. Consequently, effective action is most likely to occur locally and most likely to be useful if the state and national pictures are clearly in mind.

Long-term and sustainable populations of native fauna, especially those that are iconic, threatened, or are of economic value, is an aspiration of rural communities. The koalas of Gunnedah fit this category perfectly because Gunnedah was identified in the 2006 state-wide survey of koalas as the most substantial population west of the Great Dividing Range, and was the population that showed the greatest expansion over the previous 20 years. Further, the koala was used as the standard-bearer in the 'Bearcare' program, run jointly by the then Soil Conservation Service and National Parks and Wildlife Service. The program primarily aimed to plant trees and shrubs to prevent rising soil salinity, but had a secondary objective to benefit koalas, because many of the trees planted were koala trees and expanded their habitat. The joint LPLM and OEH program 2008-2011 has demonstrated that this was a well-conceived and successful program. The initiatives proposed in this paper capitalise on that community commitment by recognising that when a program offers many benefits, and can work cooperatively with the rural landholders, it can generate goodwill towards sustaining koala populations through land-restoration programs that include koala conservation objectives. There is acknowledged community interest and concern about the potential for increased mining for coal and coal seam gas around Gunnedah and the Liverpool Plains and the Pilliga forests. The wider NSW community also needs the koala management guidance that can be obtained through this initiative as a case study.

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APPENDIX 1 – A GUIDE TO SUCCESSFUL TREE ESTABLISHMENT FOR ENVIRONMENTAL PLANTINGS

The establishment of trees on farms and other sites can be used to achieve multiple outcomes including: stock shade and shelter, timber products, soil conservation, salinity mitigation, biodiversity benefits and improved soil health. Whether you are planting shelter-belts or tree lots, the key to successful tree establishment is forward planning. The most common failures in the establishment of trees are a lack of preparation, a lack of moisture and poor weed control. By following a few simple steps these problems can be overcome.

- Exclude stock – to establish a healthy and productive tree stand, treat the area as if you were planning to plant a crop or pasture. After selecting the site it is extremely important to exclude stock. Too often, the efforts that are put into correct establishment procedures are wasted by allowing stock access to the site. Fencing the site and excluding stock prior to site preparation ensures that damaging soil compaction cannot occur and that trees and shrubs are protected from the outset.
- Deep ripping – tree lines should be deep ripped six to 12 months ahead of planting. The best time to do this is during the summer months when the soil is dry as this will help shatter any compaction layer or plough pan. Deep ripping should be approximately 60 - 70 cm deep in a single rip line. It is often advisable to do the initial rip and then rip again in the same line until the required depth is reached. This method suits clay soils but if the soil type is loamy then two rip lines can be placed 20 - 30 cm apart to enable better soil moisture penetration and water retention.
- Weed control – it is crucial to spray out weeds during the six to 12 months prior to planting. A break between spraying and ripping is preferable, as this allows for root release and results in a less cloddy tilth. If the area to be planted is a cropping paddock, retain the stubble and spray with glyphosate as you would for a zero till fallow. If it is a grass paddock, then a strip of two metres should be sprayed out along each rip line. Follow up weed control is also essential after planting. Use of residual chemicals for weed control is not ideal but where there is no alternative, Simizine and Goal can be used. Seek professional advice before using residual chemicals. Selective use of glyphosate around the tree and within the row is extremely effective and cost efficient, however,

care needs to be taken so that the trees are not affected. A shrouded two metre boom mounted on a AWD quad bike to apply low volatile 2, 4D amine to control broadleaf weeds can produce excellent results. This is a deliberate strategy to allow native grasses to re-colonise the site and has been trialed and proven at the Gunnedah Research Centre and on numerous other sites across the state.

- Species mix – a range of native tree and shrub species should be used that are appropriate for the location. Be guided by the native species that occur within close proximity and on similar soils and landscape positions to the site being planted. There may be occasions where non-endemic native species may need to be incorporated in the planting. Always seek advice before selecting the species mix. It is best to plant these in such a way as to promote a diverse canopy and this will provide multiple benefits. I often use a mix of up to 16 tree and understorey species.
- Planting density – row spacing and distance between trees and shrubs is crucial. Generally the intermixing of trees and shrubs is the best option to produce a less regimented planting. Trees and shrubs in these plantings are often planted too close together and far in excess of the density of naturally occurring native woodland communities. This will depend on the topography, soil type and annual rainfall. For example, where the annual rainfall is 650 mm/a, spacing the rows seven metres apart with six metres distance between trees/shrubs within the row works out at approximately 200 stems/ha and allows the trees to grow relatively unimpeded. Such a planting density also allows native grasses to re-colonise and provide sufficient ground cover between the trees and shrubs. In farm forestry situations where plantings range from 600 - 1200 stems/ha, bare ground can result. Block plantings are preferable to two, three or four row windbreak plantings..
- Planting – planting of tube-stock is done manually, and a planting shovel with a tapered end is the preferred tool. Planting guidelines can be obtained from State Forest Nurseries and tube-stock suppliers. In most situations, particularly in the drier rainfall areas, it is a sensibleoption to form a dished area around the plant to allow rainfall to collect and be retained. If the soil type is prone to water-logging then the depth of the dished area should be minimal. Mortalities from weed competition and lack of moisture tend to be more of a concern than water-logging. When establishing larger areas the use of machine driven planters is another option but site preparation can be quite different than the methodology described here. Seek expert advice if using this option.
- Watering – normally an initial watering immediately after planting the tube-stock is required. This will depend on stored soil moisture and if significant rain is imminent. Depending on soil moisture and climatic conditions, another one or two water applications may be required. This is generally enough to ensure successful establishment, even in a drought year. UV treated plastic tree guards need to be used with the bottom turned inside up to capture rainfall. This creates a microclimate that favours the tube-stock, particularly during the summer months. It is also recommended that approximately ¼ bale of hay, (more if hay is not a limitation), be placed around the tree guard because this suppresses weeds and conserves moisture. It also makes it easier to spray around the tree with glyphosate. The taller UV guards and three bamboo stakes are definitely preferable to milk cartons as they can be used two to three times which reduces the cost of establishment. They also make it difficult for hares and rabbits to damage the tube-stock. Sometimes kangaroos and wallaroos may also damage the trees, especially during drought years.

Other agencies such as State Forests, Landcare, Greening Australia and Greenfleet have their preferred methods. However, the method outlined above has the advantage that it is relatively cheap, simple and effective and has been proven at a range of sites across the sheep/wheat belt of NSW.

Habitat reconstruction at Gunnedah Research Centre, Gunnedah. New South Wales

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Introduction

In 1943 the NSW Soil Conservation Service purchased a 214 ha property 6 km south of Gunnedah to demonstrate how severely degraded and eroded farmland could be rehabilitated using soil conservation earthworks and improved farming methods. The level of degradation was so severe that one significant rainfall event resulted in the adjacent main rail line being blocked by soil eroded from the property.

The Gunnedah Research Centre (the Centre) has evolved from its initial tenure as a farming property in 1905 to the present day property which has been used for research as well as production of wool, fat lambs, cattle and grain. Since 1991 a series of habitat reconstruction trials has been undertaken. At present the 90 ha of available grazing country has 20 ha of habitat reconstruction sites, with the remaining 70 ha planted with a combination of native and semi-tropical perennial grass pasture. The remainder of the property consists of steep hills of the Porcupine Range where the native vegetation has been left to regenerate naturally.

Background

In December 1988, it was evident that many of the River Red Gums (*Eucalyptus camaldulensis*), had been severely browsed by Koalas (*Phascolarctos cinereus*) resulting in a serious decline in tree health. Replacement trees were planted along the fence lines but it was soon realised that more needed to be done.

In 1991, a 1 ha direct seeding trial was initiated using one kilogram of mixed native species, including 635 g of *Eucalyptus* species - approximately 200 000 seeds - but only 12 trees became established. In 1993, the first of a sequence of habitat plantings using tubestock was commenced, as well as direct seeding understorey species. Additional plantings were undertaken in 1995, 1998, 2001, 2003, 2004 and 2005. It is intended to establish an additional 10 ha of plantings to connect the present sites to native vegetation on the Porcupine Range.

Lessons learned

From the initial direct seeding trial in 1991, it was soon realised that the smaller seeds such as *Eucalyptus* were difficult to establish locally, while the larger seeds, such as the acacias, were easier to establish. That is why tubestock are used for canopy species, and direct seeding for the establishment of understorey species. Key actions that have led to the successful establishment of the plantings include:

- excluding stock and fencing the area to be planted
- deep ripping the tree lines – try to do this when the soil is dry as that will shatter any compaction layer
- weed control – spray out rip lines to build up soil moisture 6 to 12 months prior to planting
- choosing a species mix that best fits the local plant communities – up to 16 different species have been used at the Centre, including larger trees as well as understorey species. The range of species chosen to suit the position in the landscape has been important for the survival of plantings during extended drought
- planting density and method is important and can vary depending on geographical location. In the sheep/ wheat belt a maximum of 200 stems/ha, including both overstorey and understorey species, with spacing of 6 m between stems and 7 m between rows worked best
- post planting - water if needed, control weeds, and use hay mulch to suppress weed competition and to conserve soil moisture. If stock are to use the plantings they should be managed carefully and introduced for only short periods at a time.

These actions maximised the establishment success and growth rate of the vegetation, and also created a floristically diverse and structurally complex vegetation that has increased the habitat value for a range of fauna. Over time the ground cover has developed into a mosaic of leaf litter under and around the trees, and native grasses in the open spaces, benefiting a range of ground foraging birds. Fallen branches have created additional habitat complexity.

Common Dunnart captured in the 2001 plantings. Photo: John Lemon

The habitat reconstruction sites have been used extensively as a demonstration site and for local field days, encouraging other landholders to undertake revegetation projects. More detailed information on the methods used at the Centre is contained in a Guide to successful tree establishment for environmental plantings which is available from the corresponding author on request.

Monitoring and research

Part of the success of the habitat reconstruction sites has been the inclusion of a number of research and monitoring activities. Prior to the establishment of these sites, baseline soil cores were taken to enable us to compare changes to soil health over time. Initial results showed that the plantings have resulted in improved soil organic matter and soil fertility (Wilson et al. 2002). Likewise, initial surveys of the groundcover vegetation showed that it is possible for a diversity of native grasses to recolonise sites that are planted with native vegetation (Nadolny and Lemon 2004).

Biodiversity audits were commenced in 1998 and have taken place each spring and autumn; most recently in April 2012. Many reptiles and frogs have been trapped using small mammal traps (Elliott traps) and pitfall traps. The House Mouse (*Mus musculus*) has invaded the sites but it was not until 1300 trap nights had been completed that, in autumn 2010, a male Common Dunnart (*Sminthopsis murina*) (a small, insectivorous marsupial about the size of a mouse) was captured. This was in the 9-year-old (2001) plantings, and Common Dunnarts have continued to be recorded in the 1998 and 2001 plantings.

Bird surveys were undertaken in 2000–2001 (Martin et al. 2004) and resurveyed in 2011–2012. Even during the surveys in 2000-2001, when the planted vegetation was only 3-8 years old, 55 bird species were recorded. Following the 2011-2012 surveys, an additional 11 species were recorded in the plantings and the numbers of birds (individuals per area) increased by nearly 40%. A number of threatened or declining birds have been recorded in the plantings: Glossy Black-Cockatoos (*Calyptorhynchus lathami*) were sighted in 2004 and 2008; Speckled Warblers (*Pyrrholaemus sagittatus*) and Painted Honeyeaters (*Grantiella picta*) have also been observed.

A tagged Koala in the 1993 plantings. Photo: John Lemon

Another positive outcome of the plantings is their utilisation by Koalas, as we discovered during a three year koala project (2008-2011) using radio-tracking collars, including GPS units which recorded Koala locations every 4 hours.

The value of this monitoring data for rehabilitation during and after major landscape changes, such as from mining, are now apparent (Lunney et al. 2012).

Conclusions

The major achievements of the Gunnedah Research Centre plantings are:

- the re-colonisation of the sites by native grass species
- the improvement in soil health
- the utilisation of the site by a range of animals, including threatened species
- the importation of additional native understorey species by birds after the seeds passed through their digestive system
- the ability to utilise the plantings for animal production and shelter.

The take home message from this research is that it is possible to achieve effective restoration outcomes, even on sites that have a long history of landscape degradation. It is possible to have a multiplicity of biodiversity, environmental and production benefits with careful planning and maintenance. The ability to use the sites for animal production and shelter, in addition to the environmental benefits, makes this an attractive package for landholders and other stakeholders. The lessons learned from the habitat reconstruction sites at the Centre have contributed towards the establishment of further revegetation sites across the sheep/wheat belt.

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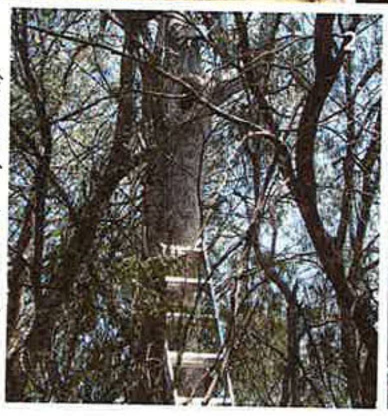


Photos 1-2 by John Lemon, 3-8 by Dan Lunney.

1 - 2. A KOALA HIDING IN A TREE HOLLOW ON A HEATWAVE DAY IN GUNNEDAH IN NOVEMBER-DECEMBER 2009. This is an extraordinary sight, and so rare that it is worth recording. It was found because it was wearing a radio-collar and John Lemon was tracking the koalas to check on their well-being. The first photo shows the ladder on the tree leading to the hollow, the second is the koala in the tree. The koala survived.

3. WHILE WE WERE RADIO-TRACKING IN DECEMBER 2009 IN GUNNEDAH, we found a limp koala lying at the base of a tree. The farmer who owned the land said that if it had been one of his stock, he would have shot it to put it out of its misery. Instead, we took it to the local veterinarian (David Amos), who revived it with 2 litres of saline solution over two days. This means about 25 % of body weight in fluid was needed to enable the koala to recover. David Amos said that without the drip it would have died of dehydration. It was released five days later.

4. KOALA BEING TREATED BY GUNNEDAH VETERINARIAN DAVID AMOS FOR DEHYDRATION. David Amos commented at the time that koalas would be "dropping like flies" from the heat. Photo, December 2009.

5. KOALA IN A LARGE RIVER RED GUM *EUCALYPTUS CAMALDULENSIS.* The next steps in the research in Gunnedah are to determine the night v day tree preferences and tree preferences during drought. Shade trees are likely to be more important than has been recognised.

6-8. A SEQUENCE SHOWING A KOALA RESPONDING TO WATER BEING SPRAYED ON ITS NOSE IN A HEATWAVE IN DECEMBER 2009. The koala was clinging to the tree near its base. John Lemon sprayed water on the koala's nose, the koala left its tree and moved to John Lemon, and drank from the spout of the water bottle. John Lemon tried to move the bottle to refill it, but the koala grasped his hand. The koala then moved through the fence to keep drinking. This is such a remarkable sequence of events for a wild koala that it worth recording both in words and photos. This was certainly a desperate act by a thirsty koala. Note the dry grass around the tree.

CLIMATE CHANGE AND KOALA POPULATIONS:

The likely impact of rising levels of carbon dioxide and heat stress, with implications for adaptation

The problem

Koalas *Phascolarctos cinereus* are specialised, folivorous, arboreal marsupials that cannot avoid extremes of the weather by going into torpor, flying, or nesting in hollows. Consequently, they look like prime candidates to suffer the impact of climate change. This paper not only examines this speculation, but moves to the next step of considering how koalas might adapt to climate change and how we, as koala managers, can adapt our management strategies to cope with these changes.

The formal government acknowledgement of the problem and the corresponding actions

a) In NSW, under the *Threatened Species Conservation Act 1995*, Anthropogenic Climate Change is listed as a key threatening process. Also, the koala is listed as a threatened species, and the *2008 NSW Koala Recovery Plan* addresses this issue under the heading "Severe weather conditions."

b) At the Commonwealth level, there is a *National Koala Conservation and Management Strategy (2009-2014)* that identifies the threats including climate change, and the actions to address them.

c) Our response: Both these formal statements identify the impact of climate change and point the way to adaptation strategies. In this paper, we recount our current work and conclusions from quite disparate strands of inquiry and weave them together to consider how we can mitigate the impact on a real landscape that is known koala habitat and that is under threat.

Our recent and current research

a) The indirect effects from rising levels of carbon dioxide

In this section we discuss the indirect effects of climate change – how increasing concentrations of atmospheric CO_2 may reduce the availability to koalas of the nutrients in *Eucalyptus* foliage.

Although several studies indicate how elevated CO_2 concentrations influence the chemical composition of eucalypts, using this knowledge to understand koala populations is hampered by our poor understanding of the links between nutrition and population dynamics of wild herbivores.

Degabriel *et al.* (2009) addressed this problem by comparing the influences of total nitrogen (N) and available N on reproduction by common brushtail possums inhabiting savannah woodland near Townsville. Mothers with ranges that had higher mean foliar concentrations of available N produced more young that grew faster. If these patterns reflect how populations of other folivorous marsupials respond to changes in the availability of foliar nutrients, then we should be better able to predict how changes in foliar nutrients associated with elevated CO_2 might affect populations of koalas.

Manipulative experiments indicate that increasing concentrations of atmospheric CO_2 can change many aspects of plant composition. These data, however, come predominantly from potted plants growing in glasshouses, but increasingly there are more realistic experiments with plants growing in the ground via open-topped chambers in which the CO_2 concentration around the individual plant is controlled.

Although no study has looked specifically at the effect of elevated CO_2 on available N, studies by Lawler *et al.* (1992) of *E. tereticornis*, Gleadow *et al.* (1996) of *E. cladocalyx* and McDowell (unpublished) of *E. ovata* measured some elements of available N in plants growing at elevated and current atmospheric CO_2 concentrations. In each study, foliar N in plants subjected to elevated CO_2 concentrations (796-804 ppm) declined by about 30 % relative to controls (352-400 ppm).

Taken together, these results suggest that, largely due to declines in total N and, to a lesser extent, a rise in the concentrations of tannins and other phenolics, available N should decline in plants growing under elevated CO_2. This suggests that aspects of leaf chemistry known to be associated with reproductive output of free-ranging folivores will change as atmospheric CO_2 concentrations rise. Thus, we could infer that elevated CO_2 will lead to significant declines in the populations of folivorous marsupials such as the koala.

We suggest two conservation approaches: (i) identifying and protecting populations of koalas on fertile sites and (ii) moving more fertile sites into the conservation estate and rehabilitating those sites with an appropriate mix of tree species and genotypes. These actions are not beyond our capacity as a society.

b) Heatwave in Gunnedah

In our current field study in Gunnedah, north-west NSW, a DECCW contingent, in conjunction with the University of Sydney, is working with Liverpool Plains Land Management to capitalise on a 1990s environmental plantings of local trees and shrubs to prevent the water table level rising in the face of a salinity crisis. The project involves catching and releasing koalas, after fitting them with a collar with a radio-tracking transmitter that includes a GPS unit that records the koalas' locations every 4 hours. In November and December 2009 there were extended heatwaves at the end of a long drought. They had visible and immediate impacts on the koalas. Our photos of this remarkable event tell part of the story of the impact of the heatwaves. On one farm, where we were radio-tracking, the farmer had noticed that 6 of a group of 20 koalas were dead on the ground. Of our 15 radio-tracked koalas, 4 suffered from dehydration; 2 died, the other 2 needed veterinary treatment - saline solution to replace lost fluids.

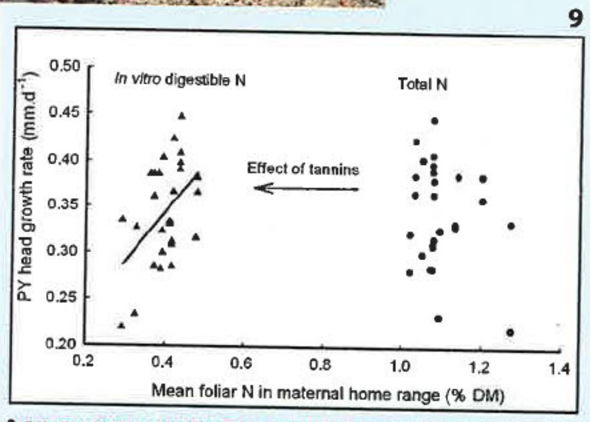
If these figures are indicative of the entire Gunnedah koala population, then about a quarter of all the local Gunnedah population would have perished in these heatwaves. Thus, a combination of drought and heatwave proved to be lethal. Droughts will increase in the climate change scenarios for most of the range of the koala (CSIRO 2007). Heatwaves will also rise in frequency. Consequently, tree plantings for koalas will now need to consider trees for water content and shade, not only for food.

Discussion

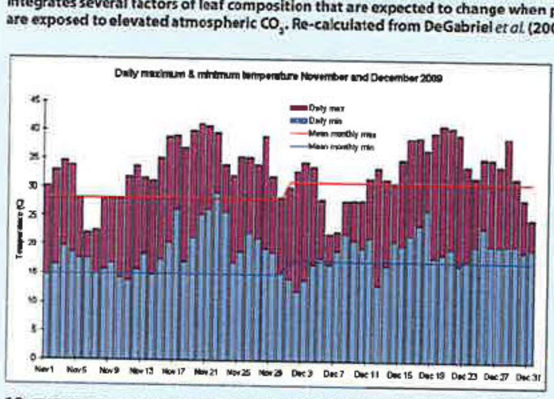
The koala already faces a powerful set of threats, such as loss of habitat, disease, fire, dogs and vehicles. Climate change will compound these stresses, because koalas will need to search further afield for appropriate trees.

In south-western Queensland, a heatwave and drought in 1979–80 resulted in the death of 63% of the koala population (Gordon *et al.* 1988). The koalas which survived were those living in good quality habitat along permanent watercourses. In the sub-optimal habitat, the trees lost their leaves and the koalas were left with no food or shelter. Ellis *et al.* (2010) found in Blair Athol in the Brigalow Belt of central Queensland that koalas adapt their behaviour. They use shady trees during the day, but might also employ physiological adaptations to access sufficient water for evaporative cooling during periods of hot dry weather. The findings in Gunnedah extend these Queensland observations and demonstrate the lethal impact of heatwaves during drought on koalas. Studies of changes in CO_2 concentrations add a powerful new dimension by pointing out that leaf quality will deteriorate due to the predicted rise in carbon dioxide levels. This is vital information for landscape managers undertaking restoration programs.

For restoration to be effective, it will need to take into account the pattern of koala movement across the landscape and will need to provide for the expected increases in droughts and heatwaves. Research will be needed to assess which trees are selected by koalas in extreme conditions. This is where the leaf chemistry story will play an increasingly important role by assisting in tree selection for restoration projects.



9. RELATIONSHIP BETWEEN HEAD GROWTH RATES of pouch young (PY) of 13 female common brushtail possums and mean in vitro digestible nitrogen (N) concentrations or mean total N concentration of foliage from the home range of each female (P = 0.014, n = 27 pouch young). The difference between the total N and in vitro digestible N concentrations is attributed to the effect of tannins although a small proportion of the difference results from N bound in the cell-wall matrix. Digestible or available N integrates several factors of leaf composition that are expected to change when plants are exposed to elevated atmospheric CO_2. Re-calculated from DeGabriel *et al.* (2009).



10. THE HEATWAVE IN GUNNEDAH IN NOVEMBER AND DECEMBER 2009. The data used were obtained from Bureau of Meteorology and came from the Gunnedah Resource Centre, where records go back to 1948. John Lemon is the current collector of these data, and here the details matter. The monthly averages show a slight increase in temperature for both minimum and maximum, but the daily readings show how the impact of heatwaves, with their successions of hot days, forced the koalas to seek free water, or suffer from dehydration. Figure prepared by Corinna

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