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# Mixed-species plantations: Prospects and challenges

J. Doland Nichols *, Mila Bristow, Jerome K. Vanclay

*Southern Cross University, Lismore, NSW 2480, Australia*

**Abstract**

About 2% of English-language literature on plantations deals with mixed-species plantations, but only a tiny proportion (<0.1%) of industrial plantations are polycultures. Small landholders are more innovative, with 12% of Australia's farm forestry plantations under mixed-species plantings, and 80% of Queensland's farm forestry as polycultures. We examine reasons for this discrepancy, and explore the history, silviculture and economics of polycultures. Financial analyses suggest that a yield stimulus of 10%, depending on product and rotation length, may be sufficient to offset increased costs associated with planting and managing a mixed-species plantation, a stimulus that has been demonstrated in many field trials. We conclude that the main obstacle to commercial uptake of polycultures in industrial plantations may be the lack of operational-scale demonstrations coupled with reliable financial analyses.


*Keywords:* Monoculture; Polyculture; Uptake; Adoption; Financial analysis

## 1. Introduction

There is wealth of research espousing the benefits of mixed-species plantings (e.g., Wormald, 1992; Ball et al., 1995; Dupuy, 1995; Hartley, 2002; Kelty, 2006; Erskine et al., 2006; Forrester et al., 2005), but a paucity of industrial polyculture plantations demonstrating commercial success. In this paper, we examine and seek to explain this discrepancy. We consider the impetus for mixed plantings, the benefits and costs, and explore the current status of commercial uptake of mixed-species plantings.

## 2. Calls for mixed plantings

Within the community of mixed-species researchers, it is easy to gain the impression that there is widespread support and demand for mixed-species plantations, but this is not generally so in the case of commercial plantations for timber production. There is little doubt that mixed-species plantings are preferable to monocultures for restoration activities (Lamb, 1998; Hooper et al., 2005), but the case is not so clear with commercial plantations for timber production. Table 1 demonstrates the results of a series of searches for information relating to ''plantation and timber'', contrasted with equivalent searches for ''plantation and timber and mixed-species'', to illustrate the relative level of interest in mixed-species enterprises for timber production. Table 1 shows that within a range of well-known databases, mixed-species plantations occupy only about 2% of the entries. The summary in Table 1 surveys only English-language material, and is influenced by the chosen search terms (cf. lumber versus timber; polyculture versus mixed species). The use of the north-American term ''lumber'' and the European phrase ''close to nature silviculture'' as alternatives did not noticeably influence the percentages reported in Table 1. Thus, Table 1 should offer a reasonable indication of the level of interest in mixed species production.

The great disparity between the number of entries in these databases is noteworthy. CAB Direct, publisher of *Forestry Abstracts*, can be expected to have more entries than the more generic Institute for Scientific Information (ISI), but the disparity between CAB Direct and Google Scholar (GS, available at scholar.google.com, an internet search engine confined to scholarly literature) is surprising. This reveals that much of the mixed-species literature is on the fringe of academia, considered noteworthy by GS, but not by CAB. Of the 879 references returned by GS, 360 contained 'Australia' as an author address, or in the subject material. Similarly, of the 37,700 references returned by Google, 989 have an Australian domain (.au; cf. 391 from .ca [Canada], and 321 from .us [mainly the US federal government]). This indicates that Australia is a major player in mixed-species research and debate, and offers an interesting case study. Table 2 examines

* Corresponding author. Tel.: +61 2 6620 3492; fax: +61 2 6621 2669.
*E-mail address:* dnichols@scu.edu.au (J.D. Nichols).

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Table 1
Relative frequency of mixed-species entries in popular databases (based on searches for ‘‘plantation and timber and mixed-species’’ on 10 March 2006)

| Database and search terms | Plantation and timber | Plantation and timber and mixed species | Percentage |
|---|---|---|---|
| Google.com | 2370000 | 37700 | 2 |
| Scholar.google.com | 19200 | 879 | 5 |
| CAB direct | 1277 | 11 | 1 |
| ISI web of knowledge | 267 | 6 | 2 |

internet domains that display material relating to mixed-species plantations, both globally and within Australia.

Domains containing .com (or national variants, including .com.au and .co.uk) have the greatest number of mixed-species documents, but relatively few (525) occur at the top-level domain of .com; most occur in national sites (e.g., .com.au). The number of hits in this category is misleading, because the count is contaminated by, e.g., repeated counts of the same scientific paper displayed by different service providers (CSA, Ingenta, JSTOR, ScienceDirect, etc.). However, Table 2 does reveal that Australia has a relatively large proportion of the global mixed-species activity, and that government agencies (those with .gov domains) are major players in promoting the mixed-species message on the internet.

Despite the high score attained by government agencies in Table 2, it appears that in Australia, they do not ‘‘walk the talk’’. Table 3, a summary of the National Plantation Inventory (Parsons and Gavran, 2005), indicates that Australia has only 359 ha of mixed-species plantations, of which 305 ha (85%) is privately owned, and planted since 1995. It is not possible to compare this with other nations, because the FAO Forest Resource Assessment does not discriminate between mixed and monoculture plantations. Australian State Governments own about half the plantations in Australia, but only 4 ha of mixed-species plantings (Parsons and Gavran, 2005). However, Table 3 is misleading, because it focuses on industrial plantations and omits farm forestry which contributes the bulk of the mixed-species plantings in Australia (Table 4, Stephens et al., 2003).

The National Farm Forest Inventory (Table 4, Stephens et al., 2003) illustrates that farmers counter the industrial trend towards monocultures, and plant a substantial proportion of mixed plantings (12% nationally). The trend varies by state: in Western Australia, 92% of farm forestry plantings are hardwood monocultures; in South Australia and Victoria 55% are softwood (*Pinus radiata*) monocultures, whereas in Queensland 81% are mixed-species plantings. The largest area of mixed plantings is in New South Wales, with 2700 ha of mixed-species plantings on private farms.

Another insight into current plantation activity can be gained from Product Rulings issued by the Australian Taxation Office. Plantation companies seeking private investment may seek a Product Ruling to clarify the tax position for investors, and these are public documents. The Australian Tax Office currently has 93 such Rulings relating to timber plantation (Table 5); of these, all but three relate to monocultures (or in the case of sandalwood, a host plant plus the intended crop). The three polyculture Rulings involve two species planted in alternate rows by BioEnergy Australia (Table 2). Table 5 overstates the real position of mixed plantings, because it does not take areas into consideration, and Rulings relating to monocultures tend to refer to larger areas than those relating to mixed plantings. Clearly, investors and industry currently do not see great advantages in species mixtures. Why is it that there is so much mixed-species literature (Tables 1 and 2), but so little activity on the ground (Tables 3 and 5)?

Several Australian non-government organisations (NGOs) have called for greater emphasis on mixed-species plantations.

Table 2
Sources of internet-based material on mixed-species plantings (based on searches for ‘‘mixed-species and plantation and timber’’ on 10 March 2006)

| Domain | Hits | Example | Typical themes | Common contaminants |
|---|---|---|---|---|
| *Global* | | | | |
| com., co | 13965 | SunWood Group (a Thai teak plantation), Panama Teak Forestry | Investment prospectus | Scientific papers hosted by commercial publishers |
| .gov | 9420 | ACIAR; Forest Research, UK | Development assistance projects | Timber sales announcements and price data |
| .org | 883 | Forest Stewardship Council, Friends of the Earth Europe | Lobbying for mixed plantings | Scientific publications (e.g., http://www.doi.org) |
| .edu., ac | 525 | Harvard Forest, University of Wales | Education, research, demonstration | Consultancy services, natural mixed species forests |
| *Australia* | | | | |
| .com.au | 143 | BioEnergy Australia, EcoForest Limited | Investment prospectus | Timber sales announcements |
| .gov.au | 591 | Rural Industries R&D Corporation, Dept Primary Industries Queensland | Farm forestry manuals | Natural mixed species forests |
| .org.au | 137 | Australian Conservation Foundation, The Greens (Political Party) | Policy statements | Restoration plantings, not timber plantations |
| .edu.au | 116 | Southern Cross University, University of Melbourne | Education, research and publications | Natural mixed species forests |

Table 3
Industrial plantations in Australia (Parsons and Gavran, 2005)

| Plantation | Area (ha) | Proportion (%) |
|---|---|---|
| Hardwood (*Eucalyptus* spp.) | 469117 | 33 |
| Softwood (*Pinus* spp.) | 947821 | 67 |
| Unknown | 462 | 0.03 |
| Mixed | 359 | 0.03 |
| Total | 1417761 | 100 |

Table 4
National Farm Forest Inventory (Stephens et al., 2003)

| State | Hardwood | Softwood | Mixed | Unknown | Total | % mixed |
|---|---|---|---|---|---|---|
| NSW and ACT | 388 | 3881 | 2698 | 915 | 7862 | 34 |
| Queensland | 253 | 378 | 2660 | 0 | 3292 | 81 |
| Victoria | 7584 | 11467 | 2002 | 33 | 21086 | 9 |
| SA and NT | 2036 | 3367 | 747 | 0 | 6150 | 12 |
| WA | 11542 | 850 | 104 | 0 | 12496 | 1 |
| Tasmania | 11700 | 4400 | 0 | 0 | 16100 | 0 |
| Total | 33504 | 24343 | 8190 | 948 | 66983 | 12 |

The Australian Conservation Foundation has called for ‘‘A forest industry restructuring package containing an accelerated transition towards ecologically sustainable farm forestry and mixed species plantation production of timber . . .’’ (Krockenberger et al., 2000, s. 14). The NSW Nature Conservation Council (1991, s. 7) has expressed the view that ‘‘Plantations, preferably of mixed species, indigenous trees, are seen as a preferred source of timber for wood and paper products. . . Government funded research on plantations of local native species, and on mixed species plantations should be expanded.’’ The Greens (political party) argued that ‘‘The [NSW] wood needs should be met from regrowth forests not needed for conservation, reforestation, woodlots and mixed species plantations’’ (Greens, 2003, s. 2.2), and that governments should foster ‘‘private capital investment in reforestation, woodlots and mixed species timber plantation development for sawlogs on private lands’’ (Greens, 2003, s. 3.2.4). These calls have not been renewed, suggesting that NGOs may have moved on to other issues. These NGOs have not developed a case for these arguments, apparently assuming that the benefits are self-evident. Others have offered arguments both against monocultures (e.g., Baltodano, 2000; but see Canell, 1999 and Bowyer, 2001) and in favour of polycultures (e.g., Ball et al., 1995; Hartley, 2002; Kerr, 1999), but usually offer environmental arguments, and the economic case, critical for commercial uptake of polyculture plantations is rarely developed.

Table 5
Current Product Rulings issued by the Australian Taxation Office (ATO)

| ATO category | Number | Species | Silviculture |
|---|---|---|---|
| Blue gums | 23 | *E. globulus* | Monoculture |
| Other eucalypts | 16 | *E. saligna*; *E. nitens* | Monoculture |
| Sandalwood | 15 | *Santalum album* or *S. spicatum* and host | Bi-culture |
| Paulownia | 12 | *Paulownia tomentosa* | Monoculture |
| Pine | 10 | *Pinus radiata* | Monoculture |
| Acacia | 5 | *Acacia mangium* | Monoculture |
| Teak | 3 | *Tectonia grandis* | Monoculture |
| Oak | 3 | *Casuarina cunninghamiana* and *Grevillea robusta* | Bi-culture |
| Mixed | 2 | *C. citriodora*, *E.globulus*, *E. nitens*, *E. dunnii*, *E. moluccana*, *P. radiata* | Monoculture |
| Oak | 2 | *Casuarina cunninghamiana* | Monoculture |
| Mahogany | 1 | *Swetienia macrophylla* | Monoculture |
| Willow | 1 | *Salix babylonica* | Monoculture |
| Total | 93 | | |

Note that the ATO ‘mixed’ category is not a true polyculture, but offers investors the choice of two to three species planted in monocultural blocks, presumably to spread risks.

This discrepancy between calls for, and establishment of mixed-species plantings suggests that there may be a lack of communication, a lack of knowledge, financial obstacles or logistical difficulties in establishing polycultures. These possibilities are examined in turn.

## 3. A brief history of mixed plantings

It is useful to briefly review the history of mixed and monoculture plantings, because many foresters hold the view that monocultures are the only way to successfully grow industrial timber. Certainly, monocultures have a long history, as the earliest recorded monoculture dates from 1368, when several 100 acres of the Lorenzer Forest near Nuremberg was sown with *Pinus sylvestris* to provide industrial timber (Toumey and Korstian, 1942). Monocultures are successful in efficient production of timber (Cossalter and Pye-Smith, 2003), have high resilience (Powers, 1999), and when well-managed, show no evidence of productivity decline (Powers, 1999; Evans, 2005).

However, mixed-plantings have also been common and successful in many situations throughout history. Larch (*Larix* sp.) has been used extensively in mixed stands in Europe with pine (*Pinus* sp., Schotte, 1917), with alder (*Alnus* sp., von der Schulenburg, 1958), with oak (*Quercus* sp.) and beech (*Fagus* sp., Stern, 1988), and has been financially important in providing an early income stream (Kiellander, 1965; Møller, 1965). It is worth quoting from Clear (1944):

> ‘‘Foresters the world over are recognising more and more the value of a proper mixture as a factor in the successful establishment and management of tree crops. While the practise of raising mixed crops is very long established . . ., there has been a tendency to depart from this old and well tried system and to lay down extensive areas under pure spruce and pine. . .’’

Even earlier, Hayes (1822) wrote that prime hardwoods such as oak should be planted ‘‘at about twenty feet . . . the plantation should then be thickened up with other sorts of trees.’’

It is also interesting to quote from Toumey and Korstian (1937, pp. 280–287) to observe that many of the issues canvassed in this special issue have been visited in the past:

> "Although, silviculturally considered, pure crops are usually undesirable, there are often economic advantages which overbalance silvicultural disadvantages. The most important of these advantages are:

- Management is much simplified . . .
- The crop can be harvested more economically . . .
- Artificial restocking is simpler . . .

> The formation of pure stands, however, is sometimes indicative of insufficient silvicultural knowledge on the part of the forester. . . In France, where silviculture is understood and practiced, mixed-stands form about three-fourths of the forest . . . are likely to be of superior economic value as well. The more important advantages that may result from mixed crops are:

- Where a mixture is suitably arranged the site is most completely utilized. . .
- A mixture of shallow-rooted species with deep-rooted species forms a stand that suffers less from wind and more fully utilizes the soil. . .
- Fungi and insects are less harmful in mixed stands. . .
- Mixed crops are more successful on poor sites than are most pure stands. . .
- When early thinnings of a species in pure stands are of little economic value, more valuable thinnings may be realized by mixing with it a species which brings better prices in small sizes. . .
- Serious mistakes made in the selection of species for artificial regeneration are more easily corrected in mixed stands than in pure crops. . .
- A mixed stand is more easily transformed or modified to meet present or probable future demands of the market or to overcome a serious fungus or insect pest than is a pure stand. . ."

The contention that francophone foresters favour poly-specific silviculture is supported by the observation that over 14,000 ha of mixed-species plantings have been established in Côte d'Ivoire since 1930 (Dupuy and Mille, 1991).

Dawkins and Philip (1998, p. 251) asked "Why is it that foresters will not learn from others' mistakes but insist on buying their own experience? . . . Much of the blame must be on our failure to transfer research findings into field practice through the use of appropriate information technology." Perhaps what polyculture lacks is a good growers' manual (cf. Maclaren, 1993) to inspire the confidence of commercial and government forestry agencies.

## 4. Silviculture and management of mixed plantings

While there is still much to be learned, the basic silvicultural considerations for successful mixed-species plantations have been established. Forrester et al. (2006b) reviewed the literature

Table 6
Summary of projected costs and returns (AUD) from a timber plantation investment scheme (Queensland Pine Forests, 2000, p. 13)

| Project year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gross harvest proceeds | | | | | | | | | 2615 | | | | | | | | 15620 | | | | | | | 60897 |
| Revenue related expenses | | | | | | | | | 413 | | | | | | | | 1309 | | | | | | | 3911 |
| Net harvest proceeds | | | | | | | | | 2202 | | | | | | | | 14311 | | | | | | | 56986 |
| Establishment[a] /fertilizer | 3088 | | | | | | | | | 514 | | | | | | | | | | | | | | |
| Licence and management | 923 | 682 | 702 | 723 | 745 | 767 | 790 | 814 | 838 | 863 | 889 | 916 | 944 | 972 | 1001 | 1031 | 1062 | 1094 | 1126 | 1160 | 1195 | 1231 | 1268 | 1306 |
| Total operating cost | 4011 | 682 | 702 | 723 | 745 | 767 | 790 | 814 | 838 | 1377 | 889 | 916 | 944 | 972 | 1001 | 1031 | 1062 | 1094 | 1126 | 1160 | 1195 | 1231 | 1268 | 1306 |
| Net profit/cash flow | −4011 | −682 | −702 | −723 | −745 | −767 | −790 | −814 | 1364 | −1377 | −889 | −916 | −944 | −972 | −1001 | −1031 | 13249 | −1094 | −1126 | −1160 | −1195 | −1231 | −1268 | 55680 |
| Internal rate of return | 9% | | | | | | | | | | | | | | | | | | | | | | | |

[a] Establishment costs included: operations planning $24; weed control $320; seedlings $907; cultivation $240; planting $260; fertilizer $394; contingencies (2% of preceding items), plus supervision $900. Fertilizer is also applied in year 10.

on nitrogen fixing trees mixed with Eucalyptus and found that in about half of the cases the growth of the Eucalyptus was better when it was combined with a nitrogen-fixer, and in no case was it worse. Burkhart and Tham (1992) reported a similar finding for boreal species. Indications are that successful mixtures are those that have species with complementary crown characteristics that form a stratified canopy (Kelty, 1992), often comprising a taller light-demanding and thin-crowned species, and a slower-growing shade-tolerant species (Smith, 1986; Menalled et al., 1998). In some cases, it is useful to underplant the latter species, so that it benefits from a nurse crop (Simpson and Osborne, 2006; McNamara et al., 2006).

Mixed plantings may require additional silvicultural intervention not necessary in monocultures. Nichols and Carpenter (2006) found that the N-fixing tree *Inga edulis*, increased the growth of an admixed species *Terminalia amazonia*, but needed to be cut back regularly to prevent the N-fixer taking over the stand. In some instances, acacias can compete strongly with eucalypts and may need to be cut back in some instances (Forrester et al., 2006a), but as a short-lived pioneer species, may also die out before competition becomes problematic (Erskine et al., 2005). However, this is especially true where acacias occur naturally at high densities rather than being planted at a desired spacing (Hunt et al., 2006).

Mixed-species plantations may also reduce the incidence of disease or insect attack. Bosu et al. (2006) found that planting *Milicia excelsa–M. regia* in a mixture with *Terminalia superba* was effective in reducing damage from a gall-forming psyllid, but that care was needed to balance light requirements and weed competition to assure both adequate growth and low levels of insect attack. *Hypsipyla* shoot borers are one of the most serious pests of planted tropical trees in the Meliaceae, and mixtures are a commonly recommended component of an integrated pest management strategy (Montagnini et al., 1995; Speight and Cory, 2001; Floyd and Hauxwell, 2001; Griffiths et al., 2005; Opuni-Frimpong et al., 2005). There is a need to attempt more integration of pest management through the use of mixtures, particularly as interest grows in using a wider range of rainforest species around the world.

## 5. Economics of mixed plantings

It is difficult to obtain reliable financial data comparing the economics of production-scale plantations of monocultures and polycultures, and there are few publications that examine this question in detail. Whitesell et al. (1992) examined the costs of short-rotation biomass production with eucalyptus monocultures and polyculture in Hawaii, and concluded that the mill-door cost of biomass was substantially lower (22–35%) when the eucalypts were grown in a polyculture with *Albizzia*, even if the *Albizzia* wood was non-merchantable.

The projected costs and returns to commercial plantation enterprises are not often made public, but a recent prospectus (Queensland Pine Forests, QPF, 2000) provided sufficient financial data (Table 6) to allow a comparison of monoculture and polyculture plantations. The QPF scheme involved growing a *Pinus* hybrid for 24 years for the production of sawlogs and roundwood, and included two thinnings at ages 9 and 17. The scheme was expected to realize an internal rate of return (IRR) of 9%. Table 7 explores the yield stimulus that would be required to maintain an IRR of 9% for a range of possible cost increases associated with planting two species in a polyculture. The analysis presented in Table 7 overlooks the species involved, assumes that prices and the scheduling of silvicultural and harvesting operations remain unchanged, and simply examines the yield increase that would be needed to offset an increase in some of the establishment costs (e.g., an increase in the cost of planting two species instead of one species).

In Table 6, the major costs contributing to plantation establishment are the cost of seedlings, and supervision (''planning and scheduling of operations, contract tendering and field supervision and management of contractors'', QPF, 2000, p. 14). The costs most likely to vary with a mixed-species planting are assumed to be operations planning, planting costs, seedlings and cultivation. The simplest mixed-species planting in which two species alternate by rows (as is proposed by BioEnergy Australia, Table 2), should involve no additional cost apart from some operations planning. In the unlikely event that these costs doubled, a modest 0.2% increase in plantation yield would restore the IRR to the target 9%. A more intimate mixture in which two species alternate within rows may increased both planning and planting costs, but 2% growth stimulus would compensate for these additional costs. Another alternative considers twice the number of plants, included as additional rows (and thus double the costs of cultivation, plants and planting), but not yielding any merchantable product (cf. Erskine et al., 2005 found that their acacias died before the first harvest): in this situation, an 11% increase in yield would offset costs if fertilizers were used, and a 6% yield increase would be sufficient if fertilizers were no longer required. Harvesting

Table 7
Yield increase required to offset additional costs associated with mixed-species plantings

| Silviculture | Cost multiplier | | | | | Yield increase needed (%) |
|---|---|---|---|---|---|---|
| | Planning | Planting | Plants | Cultivate | Fertilize | |
| Base case: monoculture | 1 | 1 | 1 | 1 | 1 | 0 |
| Same stocking, two species alternating by rows | 2 | 1 | 1 | 1 | 1 | 0.2 |
| Same stocking, two species alternating within rows | 2 | 2 | 1 | 1 | 1 | 2 |
| Double stocking, additional rows of non-commercial 'nurse' trees | 2 | 2 | 2 | 2 | 1 | 11 |
| Double stocking, additional nurse trees, no fertilizer needed | 2 | 2 | 2 | 2 | 0 | 6 |

and marketing costs are not examined in Table 6, but a doubling of these costs is offset by a 5% increase in yield. Several studies in this special issue (Bristow et al., 2006; Forrester et al., 2006a,b; Vanclay, 2006a,b) report increased yields from mixed-species plantings well in excess of 10% (especially when eucalypts are planted with nitrogen-fixing trees), so mixed-species plantings should be commercially viable.

Despite this optimistic prognosis, commercial uptake of mixed plantings continues to be slow and erratic. For instance, EcoForest Limited (mentioned in Table 2) was set up in 1997 to establish mixed-species plantations in the Hunter Valley region of New South Wales (NSW). They issued a prospectus in 2000 seeking to raise capital through the issue of shares, but were placed in receivership in 2005 because of insufficient investment. The plantation activities of BioEnergy Australia (also in Tables 2 and 5) also appear to be limited to a single 30 ha plantation in NSW.

In Australia, there are no differential grants to favour plantations of any particular species or combination. In contrast, Europe has made direct payments available to support afforestation of eucalypt (ECU 2415 $ha^{-1}$), conifer (ECU 3623 $ha^{-1}$), and broadleaved or mixed plantations comprising at least 75% broadleaved species (ECU 4830 $ha^{-1}$, Brown, 2000). Such differentials appear to be sufficient to compensate for the additional costs involved in establishing species mixtures, and should be an effective way to stimulate more interest in polycultures.

It seems that environmentalists strongly advocate mixed plantations, and academic researchers establish trials and report their findings, while operational foresters seem largely disinterested in the topic. This analysis of advocates for, and economics of mixed-species plantations suggests that plantation managers and investors may the obstacle to adoption, and that increased efforts are needed to convince them of the potential productivity gains possible with species mixtures.

## 6. Obstacles to mixed plantings

It is exceedingly difficult to obtain reliable information about corporate decisions to plant monoculture timber plantations rather than polycultures. Field foresters often refer to logistical difficulties in dealing with multiple species, but rarely wish to be quoted. For many foresters, the monoculture system works well, and they see no compelling evidence at the operational scale to suggest that polycultures are more efficient. For others (foresters and investors), it is a question of conservative attitudes: monocultures have a good track record, so why risk something different?

It seems that evidence and education may be the limiting factor in the adoption of polyculture plantations. To advance their cause, advocates of mixed-species plantations need to foster the establishment of operational-scale examples to provide sound data, convincing evidence, and compelling demonstrations. This conclusion echoes similar calls made in other reviews of related material (e.g., Binkley et al., 2003; Hooper et al., 2005; Kerr, 1999).

## 7. Research needs

It is useful to distinguish between experiments designed to provide more information about how effective polycultures work, and operational-scale plantations that emphasize the efficient realization of polyculture benefits. The experiment designs advocated by Goelz (2001) and Vanclay (2006a,b) may advance our knowledge of polycultures, but are unlikely to convince an industrial forester that they are a practical alternative to monocultures. Thus, both innovative experiments, and operational-scale demonstrations are required.

### 7.1. Better experiments and analyses

Many questions about polyculture plantations remain unresolved, and the best way to address these issues is through innovative experiments, replicated spatially, temporally and with alternative species. At present, such experiments may not seem pressing, but climate change and escalating energy prices may impact on the efficiency of monoculture plantations and stimulate further interest in polycultures. Unresolved issues encompass some aspects that require long-term experiments to assess temporal stability, recovery from disturbance, and the detection and monitoring of any feedbacks (Hooper et al., 2005). Binkley et al. (2003; also Rothe and Binkley, 2001) have called for a coordinated, international set of experiments to provide the information base that will allow forest managers to make informed and effective decisions about the total value of mixed-species plantations and monocultures.

More work needs to be done on nutrition in mixtures of forest trees. Much of the published work deals with nitrogen dynamics, while other nutrients have received less attention. Plants (e.g., *Tithonia diversifolia*) to facilitate the availability of phosphorus, an essential plant nutrient that is limiting in many soils, have been examined in agroforestry situations (e.g., George et al., 2006; Jama et al., 2000), but have apparently been neglected in forestry polycultures. In addition, a lack of statistical power (e.g., Foster, 2001) means that many experiments are ill-equipped to resolve issues of nutrient dynamics in polycultures. Rothe and Binkley (2001) observed that there are few systematic studies of particular mixtures across soil gradients (notably Wardle et al., 1997; McTiernan et al., 1997) and that the interpretation of the literature is hampered by differing methodology, experimental conditions and confusing terminology. They called for a network of coordinated experiments including the same mixture type under similar site conditions as well as different species combinations under comparable site conditions to provide insights into nutrient dynamics in species mixtures.

Many analyses of polyculture performance rely on simple indices, and do not make full use of the information available in experimental data (Forrester et al., 2006a,b). Spatially explicit competition indices (Vanclay, 2006a,b) and regression-based analytical approaches (Forrester et al., 2006a,b) offer greater insights than conventional analyses of replacement series experiments. Replacement series experiments are conventional and convenient, but suffer several limitations, and more innovative experimental designs (e.g., Goelz, 2001; Vanclay, 2006a,b) may be more useful for some field situations.

### 7.2. Operational-scale demonstrations

It is unlikely that experiments will be sufficient to influence operational uptake of polycultures, so operational-scale plantings will be needed to demonstrate the utility of polycultures. Such demonstrations should not simply illustrate the biological performance of the trees involved, but should capture sufficient data to allow comprehensive accounting of all costs and revenues, and should include surveys of community attitudes towards the plantation at various stages of growth, so that a comprehensive analysis of biological, economic and social aspects can be completed. However, care is required to design an effective demonstration program. A review of a previous Farm Forestry Program in Australia (Race and Curtis, 1991) found that large numbers of demonstration sites had been established with inadequate consideration given to monitoring, evaluation and dissemination of findings. A recent review (Nikles and Robson, 2005) of rainforest plantings also concluded that inadequate funding, both in terms of amount and continuity, hampered the ability to ‘‘establish and properly maintain good field tests with sufficient species for a long enough period to obtain reliable data, and denied the opportunity to follow-up on preliminary insights’’. This experience provides a clear lesson with regard to future work of this kind: it needs adequate long-term funding, with clear protocols for managing changes of staff and research priorities.

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