2006

Mixed species plantations: prospects and challenges

J Doland Nichols
Southern Cross University

Mila Bristow
Southern Cross University

Jerome K. Vanclay
Southern Cross University

Publication details

Pre-print of Nichols, JD, Bristow, M & Vanclay, JK 2006, 'Mixed species plantations: prospects and challenges', *Forest Ecology and Management*, vol. 233, no. 2-3, pp. 383-390.
Forest Ecology and Management home page available at www.elsevier.com/locate/foreco
Publisher's version of article available at http://dx.doi.org/10.1016/j.foreco.2006.07.018

Forest Ecology and Management 233 (2006) 383-390.
doi:10.1016/j.foreco.2006.07.018

Mixed species plantations: prospects and challenges

J. Doland Nichols, Mila Bristow, and 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.

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. 2006b), 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.

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 two percent of the entries. The summary in Table 1 surveys only English-language material, and is influenced by the chosen search terms (cf. lumber vs timber; polyculture vs 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.

[Table 1 near here]

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 37700 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 internet domains that display material relating to mixed-species plantations, both globally and within Australia.

[Table 2 near here]

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).

[Table 3 near here]
[Table 4 near here]

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 4 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 & 2), but so little activity on the ground (Table 3 & 5)?

[Table 5 near here]

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

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.

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 hundred 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, p.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 polyspecific silviculture is supported by the observation that over 14000 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.

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 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 Osborn 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 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.

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).

[Table 7 near here]

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 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 2006; Vanclay 2006) 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 Table 2 and Table 5) also appear to be limited to a single 30 hectare 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), conifer (ECU 3623/ha), and broadleaved or mixed plantations comprising at least 75 percent broadleaved species (ECU 4830/ha, 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.

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).

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 (2006) 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.

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. 2006).

Spatially-explicit competition indices (Vanclay 2006) and regression-based analytical approaches (Forrester et al. 2006) 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 2006) may be more useful for some field situations.

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 (Nickles 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.

References

Ball, J.B., Wormald, T.J., Russo, L., 1995. Experience with mixed and single species plantations. *Common For. Rev.* 74: 301–305.

Baltodano, J., 2000. Monoculture Forestry: a critique from an ecological perspective. *In:* Tree Trouble: a compilation of testimonies on the negative impact of large-scale monoculture tree plantations prepared for the 6th COP of the FCCC. Friends of the Earth International, pp. 2-10.

Binkley, D., Senock, R., Bird, S., Cole, T.G., 2003. Twenty years of stand development in pure and mixed stands of *Eucalyptus saligna* and nitrogen-fixing *Facaltaria moluccana*. *Forest Ecology and Management* 182, 93-102.

Bosu, P., Cobbinah, J R., Nichols, J.D., Nkrumah, E.E., Wagner, M.R., 2006. Survival and Growth of Mixed Plantations *of Milicia excelsa* and *Terminalia superba* nine years after planting in Ghana. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.032.

Bowyer, J.L., 2001. Environmental implications of wood production in intensively managed plantations. *Wood and Fiber Science* 33: 318–333.

Brown, C., 2000. The global outlook for future wood supply from forest plantations. FAO Working Paper No: GFPOS/WP/03, 156 pp.

Bristow, M., Vanclay, J.K., Brooks, L., Hunt, M., 2006. Growth and species interactions of *Eucalyptus pellita* in a mixed and monoculture plantation in the humid tropics of north Queensland. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.019.

Burkhart, H.E., Tham, Å., 1992. Predictions from growth and yield models of the performance of mixed-species stands. In: Cannell, M.G.R., Malcolm, D.C., Robertson, P.A. (Eds.), The Ecology of Mixed-species Stands of Trees. Blackwell Scientific Publications, Oxford, pp. 21–34.

Canell, M.G.R., 1999. Environmental impacts of forest monocultures: water use, acidification, wildlife conservation, and carbon storage. *New Forests* 17: 239–262.

Clear, T., 1944. The Role of Mixed Woods in Irish Silviculture. Irish Forestry Journal 1(2), http://www.prosilvaireland.org/article/mixture_in_Irish_silvi.html

Cossalter, C., Pye-Smith, C., 2003. Fast-wood Forestry: Myths and realities. CIFOR, Bogor, ISBN 9793361093, 59 pp.

Dawkins, H.C., Philip, M.S., 1998. Tropical Moist Forest Silviculture and Management: A history of success and failure. CAB International, Wallingford, 359 pp.

Dupuy, B., 1995. Mixed plantations in Cote d'Ivoire rain forests. *Bois et Forets des Tropiques* 245: 33-43.

Dupuy, B. & Mille, G. 1991. Reboisement a vocation bois d'ouevre en Afrique intertropicale. FAO 98, Rome. 225p.

Erskine, P.D., Lamb, D., Bristow, M., 2006.Tree species diversity and ecosystem function: can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.013

Erskine, P.D., Lamb, D., Borschmann, G., 2005. Growth performance and management of a mixed rainforest tree plantation. *New Forests* 29:117-134.

Evans, J., 2005. Growth rates over four rotations of pine in Swaziland. *International Forestry Review* 7(4):305-310.

Floyd, R., Hauxwell, C., 2001. Proceedings of an International Workshop on *Hypsipyla* Shot Borers of the *Meliaceae* at Kandy, Sri Lanka, 20-23 August,1996, Australian Centre for International Agricultural Research, Canberra, Australia.

Forrester, D. I., Bauhus, J., Cowie, A.L., 2005. On the success and failure of mixed-species tree plantations: lessons learned from a model system of *Eucalyptus globulus* and *Acacia mearnsii*. Forest Ecology and Management 209(1/2): 147-155.

Forrester, D.I., Bauhus, J., Cowie, A.L., 2006a. Carbon allocation in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.018

Forrester, D.I., Bauhus, J., Cowie, A., Vanclay, J.K., 2006b. Mixed-species plantations of Eucalyptus with nitrogen fixing trees: a review. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.012

Foster, J.R., 2001. Statistical power in forest monitoring. Forest Ecology and Management 151:211-222.

George, T.S., Turner, B.L., Gregory, P.J., Cade-Menun, B.J., Richardson, A.E., 2006. Depletion of organic phosphorus from Oxisols in relation to phosphatase activities in the rhizosphere. *European Journal of Soil Science* 57, 47–57.

Goelz, J.C.G., 2001. Systematic experimental designs for mixed-species plantations. *Native Plants Journal* 2:90–96.

Greens, 2003. NSW Greens Policies: Forests and Wilderness (revised January 2003). http://www.nsw.greens.org.au/policies/Forests.php (verified 13/3/2006).

Griffiths, M.W., Cunningham, S.A., Wylie, F.R., Floyd, R.B., 2005. Perspectives on the management of *Hypsipyla robusta* in the Asia Pacific region. *International Forestry Review* 75(5):276.

Hartley, M.J., 2002. Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management* 155: 81–95.
Hayes, S., 1822. *A practical treatise on planting; and the management of woods and coppices*. Dublin: Samuel Jones, 8vols, ix+189 pp.
Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A,. Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs* 75, 3–35.
Hunt, M.A, Battaglia, M., Davidson, N.J., Unwin, G.L., 2006. Competition between plantation Eucalyptus nitens and Acacia dealbata weeds in north-eastern Tasmania. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.017
Jama, B., Palm, C.A., Buresh, R.J., Niang, A., Gachengo, C., Nziguheba, G., Amadalo, B., 2000. Tithonia diversifolia as a green manure for soil fertility improvement in western Kenya: A review. *Agroforestry Systems* 49(2):201-221.
Kelty, M.J., 1992. Comparative productivity of monocultures and mixed-species stands. In: Kelty, M.J. (Ed.), The Ecology and Silviculture of Mixed-species Forests. Kluwer Academic Publishers, The Netherlands, pp. 125–141.
Kelty, M. J.,1995. Plot designs for the analysis of species interactions in mixed stands. Commonwealth Forestry Review 74(4): 322-332.
Kelty, M.J., 2006. The role of species mixtures in plantation forestry. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.011
Kerr, G., 1999. The use of silvicultural systems to enhance the biological diversity of plantations in Britain. *Forestry* 72(3), 191-205.
Kiellander, C.L. 1965. Om lärkträdens egenskaper och användning med särskild hänsyn till europeisk och japansk lärk. Föreningen Skogsträdsförädling, årsbok, pp 65-99. (In Swedish with English summary).
Krockenberger ,M., Kinrade, P., Thorman, R., 2000. Natural Advantage: A blueprint for a sustainable Australia, Australian Conservation Foundation, 96 pp.
Lamb, D., 1998. Large-scale ecological restoration of degraded tropical forest lands: the potential role of timber plantations. *Restoration Ecology* 6:271-279.
Maclaren, J.P., 1993. Radiata Pine Growers' Manual. FRI Bulletin No 184, 140 pp.
McNamara, S., Duong Viet Tinh, Erskine, P.D., Lamb, D., Yates, D., Brown, S.,

2006. Rehabilitating degraded forest land in central Vietnam with mixed native species plantings. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.033

McTiernan, K.B.P., Ineson, P., Hasted, P.A. 1997. Decomposition of tree litters in mixture. Oikos, 78: 527–538.

Menalled, F.D., Kelty, M.J., Ewel, J.J., 1998. Canopy development in tropical tree plantations: a comparison of species mixtures and monocultures. *For. Ecol. Manage.* 104, 249–263.

Møller, C.M. 1965. Vore skovtræarter og deres dyrkning. Dansk Skovforening, Copenhagen, pp 175-187. (In Danish.)

Montagnini, F., González, E., Porras, C., Rheingans, R., 1995. Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest damage, and establishment costs. *Commonwealth Forestry Review* 74(4): 306-314.

Nature Conservation Council of NSW, 1991. Forest Policy (October 1991). NCC, 9 pp. http://www.nccnsw.org.au/index.php?option=com_docman&task=doc_download&gid=44

Nichols, J.D., Carpenter, F.L., 2006. Interplanting *Inga edulis* with *Terminalia amazonia* yields nitrogen benefits to the timber tree. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.031

Nikles, D.G. and Robson, K.J., 2005. Vegetative propagation and preliminary field performance of sixteen rainforest tree species in north Queensland. In: Erskine, P.D., Lamb, D. and Bristow, M. (eds) 2005. Reforestation in the Tropics and Subtropics of Australia Using Rainforest Tree Species. RIRDC Publication No 05/087, Rural Industries Research and Development Corporation, Canberra, pp. 49-68.

Opuni-Frimpong, E., Karnosky, D.F., Thakur, R., Storer, A., Cobbinah, J.R., 2005. A biotechnological approach to developing mahogany trees resistant to mahogany shoot borer, *Hypsipyla* spp. *International Forestry Review* 75(5):54.

Parsons, M., Gavran, M., 2005. National Plantation Inventory 2005 Update. Bureau of Rural Sciences, Canberra, 8 pp.

Powers, R.F., 1999. On the sustainable productivity of planted forests. *New Forests* 17, 263–306.

Queensland Pine Forests, 2000. Queensland Pine Forests Project: a growing opportunity, GRO Australia, 41 pp.

Race, D., Curtis, A., 1991. Farm forestry in Australia: review of a national program. *Agroforestry Systems* 34:179-192.

Rothe, A., Binkley, D., 2001. Nutritional interactions in mixed species forests: a synthesis. *Can. J. For. Res*. 31:1855-1870.

Schotte, G. 1917. Lärken och dess betydelse för svensk skogshushållning. Meddelande från Statens Skogsförsöksanstalt, No.13-14. Årsbok. (In Swedish with English summary.)

Schulenburg, von der, A. Fr. 1958. Om lärken och dess odling i Norden. Svenska Skogsvårdsföreningens Tidskrift, No. 4, pp 359-370. (In Swedish.)

Simpson, J., Osborne, D., 2006. Performance of seven hardwood species underplanted to *Pinus elliottii* in south-east Queensland. *Forest Ecology and Management* doi:10.1016/j.foreco.2006.05.021

Smith, D.M., 1986. The Practice of Silviculture. Wiley, New York, 527 pp.

Speight, M.R., Cory, J.S., 2001. Integrated pest management of *Hysipyla* shoot borers. In: Floyd, R., C. Hauxwell 2001. Proceedings of an International Workshop on *Hypsipyla* Shot Borers of the *Meliaceae* at Kandy, Sri Lanka, 20-23 August, 1996. Australian Centre for International Agricultural Research, Canberra, Australia.

Stephens, N., Wood, M., Allison, B., Howell, C., 2003. Farmer and landholder contributions to Australia's commercial plantations. In: B.P. Wilson and A. Curtis (eds) Agriculture for the Australian Environment. Proceedings of the 2002 Australian Academy of Science Fenner Conference on the Environment. The Johnstone Centre, Charles Sturt University, pp.190-200.

Stern, M. 1988. Hybridlärk - en sammanställning av praktiska erfarenheter och litteratur. SLU. Institutionen för skogsskötsel. Arbetsrapport, No. 24, 52 pp. ISSN 0281-7292. (In Swedish.)

Toumey, J.W., Korstian, C.F., 1937. *Foundations of Silviculture upon an Ecological Basis*. John Wiley and Sons, New York, 456 pp.

Toumey, J.W., Korstian, C.F., 1942. *Seeding and Planting in the Practice of Forestry*. John Wiley and Sons, New York, 507 pp.

Vanclay, J.K., 2006. Designing a trial to evaluate mixed plantings of forest trees. *Forest Ecology and Management doi:10.1016/j.foreco.2006.05.020*

Vanclay, J.K., 2006. Spatially-explicit competition indices and the analysis of mixed-species plantings with the Simile modelling environment. *Forest Ecology and Management doi:10.1016/j.foreco.2006.05.034*

Wardle, D.A., Bonner, K.I., Nicholson, K.S. 1997. Biodiversity and plant litter: experimental evidence which does not support the view that enhanced species richness improves ecosystem function. *Oikos*, 79: 247–258.

Wormald, T.J., 1992. Mixed and pure forest plantations in the tropics and subtropics. Rome, Food and Agriculture Organization of the United Nations.

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 & Search terms	plantation & timber	& mixed-species	Percentage
Google.com	2 370 000	37 700	2%
Scholar.google.com	19 200	879	5%
CAB Direct	1 277	11	1%
ISI Web of Knowledge	267	6	2%

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

Table 3. Industrial Plantations in Australia (Parsons and Gavran 2005).

Plantation	Area (ha)	Proportion
Hardwood (Eucalyptus spp.)	469 117	33%
Softwood (Pinus spp.)	947 821	67%
Unknown	462	0.03%
Mixed	359	0.03%
Total	1 417 761	100%

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

State	Hardwood	Softwood	Mixed	Unknown	Total	% Mixed
NSW & ACT	388	3881	2698	915	7862	34%
Queensland	253	378	2660	0	3292	81%
Victoria	7584	11467	2002	33	21086	9%
SA & 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%

Table 5. Current Product Rulings issued by the Australian Taxation Office (ATO). Note that the ATO 'Mixed' category is not a true polyculture, but offers investors the choice of 2-3 species planted in monocultural blocks, presumably to spread risks.

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* & 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 & 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		

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†/Fertilizer	3088									514														
Licence & 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%																							

† 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.

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%