Science and technology for sustainable development of plantation forests

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Summary

Industrial plantations, farm forests and tree planting for environmental benefits are links in a continuum of sustainable land use. Sustained productivity is the foundation of sustainable forestry business, even when forestry systems are designed to provide environmental services, because productivity drives key ecological processes. The critical roles of science and technology, which underpin sustainable resource development, have broadened. Important research areas in which investments would pay good returns are discussed. Research must continue to seek ways of improving management, and ways for measuring and valuing tradeoffs between different components of sustainability. Partnerships between researchers and managers need to be revitalised in order to make the best use of an information-rich environment.

Keywords: forest plantations; forest management; sustainability; research; Australia

Introduction

Planted forests are a land-use system mostly designed for long-term commercial wood production. There is a global recognition that further development of plantations and farm forests can address the increasing mismatch between wood supply and demand, and contribute to environmental solutions for salinity mitigation, biodiversity enhancement, catchment protection and carbon sequestration. In Australia, plantation forestry has become a business through commercial, land-based, public and private investments including a substantial international component.

The concept of sustainable forestry embodies a kaleidoscope of ideas and expectations, continuously reshaped through ever-changing social and political values. Multiple values, diverse expectations, the need to achieve high and predictable production, the economic realities of management, and the nature of plantation ownership all affect the pursuit of sustainability. Plantation forestry development, along with all other land-use systems, should comply with the principles of ecologically sustainable development.

Australian plantation forests occupy about 1.4 million ha, two-thirds of which is in pine. The rate of establishment of industrial eucalypt plantations increased rapidly from the mid-1990s, with a record 120 000 ha being established in 2000. Eucalypt plantations now occupy about one-third of the total plantation area. Despite considerable efforts to promote farm forestry, the area under this form of land use remains very low. These three types of resources — pine plantations, eucalypt plantations and farm forests — are at different stages of history. Their sustainable development and use present some shared and some divergent challenges.

Industrial plantations, farm forests and tree plantings for environmental benefits are essential links in a continuum of sustainable land use. Several types of plantation development to suit one or more land-use objectives are possible. The primary purpose of plantation forests, however, regardless of the size of the investment, remains commercial wood production. Even when reforestation is proposed for environmental benefits, the economic imperative leads to the conclusion that the environmental goals are likely to be met only if we can add value (including the value of forest products) to the environmental services expected of such programs.

Several issues are at the hub of sustainable resource development.

- Production forestry faces the challenge of making an increasing and sustained contribution to the national economy, and especially to regional prosperity, in a competitive global economy, while promoting environmental care and stewardship.
- Expansion of the forest area during the last decade, largely for eucalypt plantations, has been mostly around the periphery of established plantation areas. This expansion has sharpened the biophysical and social challenges to sustainability.
- Forestry, in various forms of practice, is gaining recognition as one of the potential solutions to environmental degradation affecting land, water and biodiversity. In order to realise this potential, the forest plantation industry has to venture into land

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bases and environments beyond our current experience with production forestry.
- Forestry needs to engage in and contribute to public policy debates about tradeoffs, multi-party investments and the long-term future of regional Australia.

Sustainable resource development must underpin the prospects for Australian forest plantations. In this paper, I focus on how research and development (R&D) contribute to the pursuit of sustainable forestry. This paper is not a comprehensive analysis of the multifaceted aspects of sustainable resource development. It is selective in approach, using examples to illustrate the way we can examine components of sustainability. Sustained forest productivity is the foundation on which sustainable plantation forestry and the business outcomes of forestry rest. That is so even when forestry systems are designed to provide environmental benefits, because productivity drives key ecological processes. Sustained productivity is, arguably, the best measure that integrates the functioning of plantation forests and signals the direction of change in response to management practices. Measures of productivity may include gross or net primary production, merchantable wood yield and/or carbon sequestration in the ecosystem. Thus productivity is a focusing point in this paper, but it is presented in the context of the objectives of this conference and is illustrated in Figure 1.

The concept of sustainable forestry

Sustainable resource development can be viewed in relation to the degree of alignment between the four critical variables: ecological capability of the sites and their interconnection with landscape, environmental values including soil, water and biodiversity, investment and management intensity, and economic and social benefits. A simple conceptual model of this idea is presented in Figure 1. Sustainability suffers if the alignment is poor. The alignment will never be perfect because we are unlikely to have the full knowledge, tools, investments and social agreement necessary for perfection. Sustainable resource development and environmental stewardship should be central goals of any plantation forestry enterprise. There is little future for such enterprises if their culture and management are driven by a purely extractive philosophy.

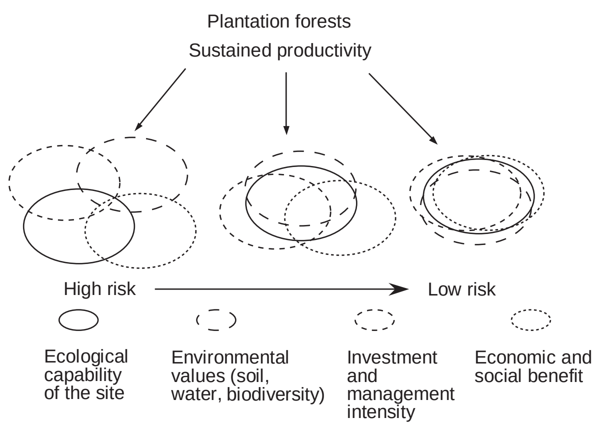

Figure 1. Plantation forestry — Interactive elements of sustainability (Nambiar and Brown 1997)

A general set of goals for plantation forestry (Nambiar 1996) is:

- To ensure that the trend in productivity is non-declining or increasing over successive harvests.
- To protect the productive capacity of the soil and off-site values including water and biodiversity in the plantation environment.
- To promote incentive, innovation and profit for the business of growing and utilizing wood.
- To improve the economic and social benefits to the community.

In many circumstances there will be a need for tradeoffs among some values. However, there are real problems to be solved on how to measure and value tradeoffs with respect to forestry as a land-use system. Success will depend on transparent, informed and shared arrangements for tradeoffs. Thus the goals of plantation forestry have widened but each business enterprise, which manages an estate, may focus on one or more of the above goals.

A framework for research

An illustration of the flow-on from R&D investments to products and services is given in Figure 2.

Benefits from research investments are derived in different ways: for example from improved planting stock, diagnostic tools and growth models, or essential information to assist balanced public discussion and policy development. To be successful, an R&D strategy in forestry must treat strategic research, applied research and large-scale application as a continuum with well-developed feedbacks. Research to solve problems facing us today, and those anticipated tomorrow, is built on the insights and experience — the intellectual assets — gained in the past. Active partnerships between stakeholders and commitments to mutual support are central to success.

Research achievements

Science and technology have underpinned sustainable plantation forestry in Australia. The following examples illustrate some of the achievements in three diverse areas.

Increased and sustained productivity of pine plantations

Radiata pine (*Pinus radiata* D. Don) plantations established in the south-east of South Australia and western Victoria are a major asset. It has been argued, without evidence, that monoculture plantations of exotic pine established on podsolised sandy soils are ecologically unsustainable. This view initially gained ground through the well-known second-rotation decline in productivity. These plantations are intensively managed to achieve high production on infertile sandy soils low in available water. Long-term explanatory research on the processes involved, and systematic application of results, produced profitable

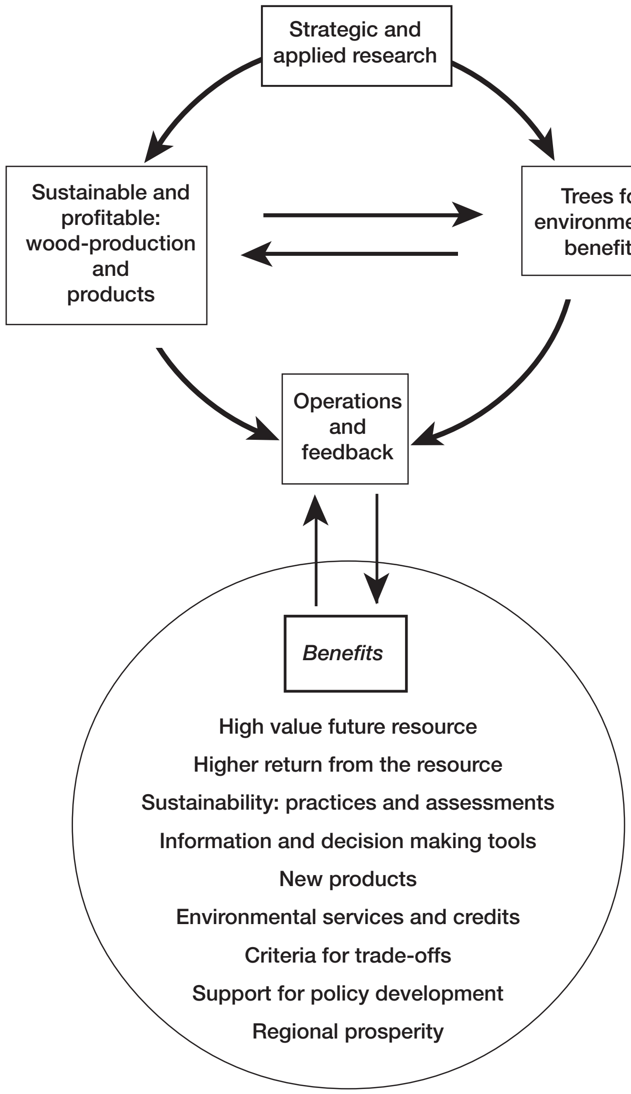

Figure 2. A framework of research and delivery of benefits

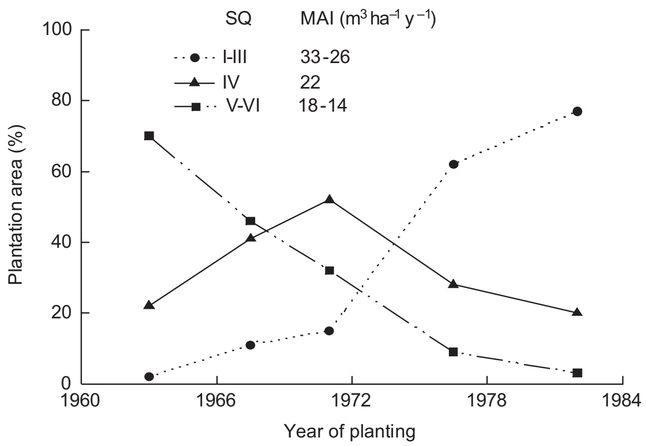

Figure 3. Long-term trends in the area classified in various site quality classes of second- and third-rotation plantations of *Pinus radiata* on podsolised sandy soils in South Australia. Data from ForestrySA (Nambiar, 1999).

management options which not only maintained yield but also enhanced it over extensive areas (Boardman 1988; Woods 1990–91). ForestrySA, the largest custodian of plantations in the region, assessed growth on their second- and third-rotation sites in 1994 according to a Site Quality scale (SQ VII (low) to SQ I (high)). The results (Fig. 3) show that in the early 1960s, about 70% of the plantation area was in the range (SQ) V–VI (MAI 18–14 m^3 ha^{-1} y^{-1}). The growth trends of subsequent plantations, planted in 1984 and measured during 1994–95, on predominantly second- and third-rotation sites, have provided a basis for upgrading the assessment of many sites from low SQ to SQ I–III (MAI 33–25 m^3 ha^{-1} y^{-1}). Carlyle and Nambiar (2001) showed that radiata pine stands growing on these sites are far more efficient in stem wood production, at a given level of nitrogen availability in the soil and the amount of annual rainfall received, than a wide range of managed conifer and hardwood stands in USA. With scientifically based management, ongoing overall improvements in wood yield are being achieved across a range of soil and environmental conditions and forest ownerships in radiata pine plantations in Australia (Nambiar 1996, 1999).

A comprehensive collaborative study by CSIRO Forestry and Forest Products and the Queensland Forest Research Institute examined the long-term impacts on important soil properties of pine forestry in the Green Triangle (south-eastern South Australia and western Victoria) and south-eastern Queensland. It was found that key properties of soils under plantations are comparable with or better than those under adjacent pasture or native vegetation (Report — Soil-based information for developing sustainable plantation forestry in Australia, Forestry and Wood Products Corporation (FWPRDC), September 2002, unpublished), attesting to the quality of management over the long term. The achievements which have underpinned sustainability have been possible through the application of multi-disciplinary collaborative research and prompt application of results through partnerships.

Genetic improvement and deployment of sub-tropical pines in Queensland

Forest managers in Queensland introduced exotic pine species to complement the indigenous hoop pine as their resource base, and supported, among other strategies, a systematic and innovative tree improvement program. The achievements which followed have been remarkable (Nikles 1996; Powell and Nikles 1996). The coniferous plantation estate in Queensland occupies about 180 000 ha of which about 45 000 ha are hoop pine. The rest is planted with exotic pines, *Pinus elliottii* (31%), *P. caribaea* var. *hondurensis* (31%) and clones of the hybrid between these two taxa (16%). In 1999–2000 all replanting after harvest (second rotation) was with the clonal hybrids. The core elements of this long-term, integrated strategy include evaluation of genetic gains under the specific soil and environmental conditions; breeding to incorporate a range of growth, adaptation and wood quality traits; inter-specific and intra-specific hybridisation; development of large-scale propagation technology, and clonal forestry backed by a sound strategy to minimise risk. The combined results of the tree improvement and deployment with appropriate silviculture have been outstanding: a reduction in the length of rotation needed to produce high-value logs from 30 to 20 y, increased productivity and quality of the resource, and extension of the boundaries of land suitable for forestry. The special feature of the Queensland program, however, is in its integrated approach to clonal forestry based on hybrids, the first in Australia. There have been other successful tree improvement and deployment programs in Australia exemplified by the Southern Tree Breeding Association for radiata pine and by CALM (WA) for *P. pinaster.*

Codes of practice for plantation forestry

A code of forestry practice is an important instrument for sustainable management. Forest management agencies in all States and Territories support codes which guide the balance between production and environmental goals. In order to achieve this balance we need sufficient knowledge about our unique ecosystems, the impact of management on ecosystem processes and an understanding of economic and social realities. A continuously improving science base and the scientific independence in the application of knowledge form the foundation of a code. Without this foundation the code becomes a set of bureaucratic rules, rather than a representation of shared values and a guide to the path of sustainability. Research has made an enormous contribution to the development of codes, and continued refinement depends on knowledge and adaptive research.

Research investments for the future

Investments in strategic R&D can be directed to one or more components of the value chain, which include growing and managing the resource, harvesting and transport, and processing wood products. Environmental stewardship is an integral part of this spectrum. The focus of this discussion is on growing and managing the plantation sustainably. Australia’s plantation resource is small in the global scale. But this resource is spread across extraordinarily diverse biophysical environments, with problems characteristic of this continent: endemic water stress; repeated severe droughts; low soil fertility; threats including fire, pests and diseases; and long distances to market. What are the major opportunities for investment in research for the future? Some important examples follow.

Genetically improved trees for future forests

Research has delivered continuous and valuable genetic gains which have benefited the pine sector, and there has been significant progress in enhancing the quality of eucalypt plantations. The next generation of advances is likely to come through the integration of genomics and quantitative genetics. This will be quite independent of what may be offered by GM technology. The science of gene discovery, function and expression coupled with advances in breeding strategy offer products including targeted trait selection for enhancing the value of the wood, hybrids suitable for plantation expansion to new areas, and methods for quickening breeding cycles. In future, delivery of high quality planting material will require a clonal propagation system. Such a delivery system is in place for pines but substantial work lies ahead for temperate eucalypts. The opportunity for clonal propagation will increase as eucalypt plantations expand in tropical and sub-tropical species.

Uniform wood for high value

A wood supplier who can make a commitment to long-term delivery against tight specifications has an advantage in the market. Ideally, future wood research needs to address uniformity over the life span of the tree, within annual growth rings and within stands. The combination of tree breeding, soil management and silviculture has revolutionised the rate of growth achievable, thereby shortening the rotation time for logs of standard size (from 45–50 y to 25–30 y in radiata pine). However, faster-grown logs have a greater proportion of juvenile wood, which diminishes product value.

The problem of lack of uniformity has been hard to study because of the difficulty in measuring key wood properties such as stiffness, microfibril angle, characteristics of cell walls and density profiles across the growth rings. The development of SilviScan for rapid examination of these wood properties at the microscopic level, and advances in near infra-red technology for their indirect assessment, have greatly enhanced our capacity to understand variation in wood properties within trees, and across breeding populations and under differing environments. Thus, an integrated approach combining these technologies with genomics and quantitative genetics has opened new opportunities for manipulating wood traits in breeding programs and for shortening breeding cycles.

We clearly need greater understanding of the genetic, site and silvicultural determinants of log and wood quality to select genetically optimal planting stock. We have the potential to link our understanding of wood quality variation to site quality (wood volume) maps, manage the stand for desired quality, segregate the logs at the forest site — using acoustic technology — for their processing efficiency, and then regulate the wood-flow precisely to the desired product line. These issues are equally important for maximising the value of both softwood and hardwood resources.

Management of soil and water

Soil

We have no choice but to use the soil resource wisely and in perpetuity, regardless of changes in land use. We are now acutely aware of the need to manage the forests, regardless of their nature and purpose, cognisant of catchment and landscape processes and function. Plantation management practices are changing at a faster pace in response to investment and market pressures. Many of these changes continually affect forest sites. They include shorter rotations, intensive management targeted to high yield, requirements to protect environmental values, and forest operations including harvesting. We need continued investments in soil research to ensure the sustainable use of soil to serve the changing management goals of production including cost of production and environmental outcomes.

Water

Few issues have evoked more questions and uncertainty in our deliberations of sustainability than those related to the interplay between plantation forests and water. This critical issue has been the focus of a national workshops of stakeholders (Nambiar and Brown 2001; O'Loughlin and Nambiar 2001) and is a topic of another presentation in this conference. Key issues where work is required include: eco-physiological relationship between site, stand and growth; drought risk management; and impacts of forestry on water resources. The last issue is the focus of much public and policy discussion. O'Loughlin and Nambiar (2001) pointed out that some arguments about the negative hydrological effects of forestry are based on the concern about 'wall-to-wall forests' displacing agriculture and those plantations maintaining full canopies. This is an over simplification. New forests are being established as discrete and fragmented tree communities across the terrain. Even where plantations occur contiguously, they exist at any given time as a mosaic of age classes, site qualities and stand densities, giving rise to a range of impacts on water fluxes. Furthermore, there is an important need to recognise the diversity of ecosystem-specific processes and the overall value of forestry in the regional economic, environmental and social contexts.

Getting more from the resource on the ground

There is a great opportunity for getting more out of the current resource by more astute management of the soil and stand. For example, there is great scope for large-scale increases in productivity of the pine plantations, without major adverse effects on wood quality, through judicious fertiliser application to 10–25-y-old stands. For the best outcome, we require a decision support system including sophisticated diagnostic techniques, models for accurate yield prediction and for scaling up information to a management unit level, more efficient fertiliser strategies, and changes in investment outlooks.

Land base and long-term productivity of eucalypt plantations

The eucalypt plantation industry, especially bluegum (*Eucalyptus globulus*) plantations, has expanded from a small initial base over the last decade. In general, industry has taken up improvements offered by R&D in areas including site selection, growth modelling, silviculture and pests and disease management. However, many decisions on site selection and management of plantations have been based on simplistic extrapolation and assumptions leading to questions about sustainability. Key questions include: What is the sustained productive capacity of the land base currently planted and the land that might be available in the future? In the absence of long-term growth data, how can we predict productivity and the response to different management options in order to make decisions now? Does fast growth equate to drought risks in Mediterranean environments? Can high value logs be produced from the resource? Answers to these generic issues are also pivotal for the development of plantation forestry in sub-tropical and tropical environments.

Managing threats from diseases and insects

Diseases

Apart from the periodic regional outbreaks of needle-cast disease caused by the fungus *Dothistroma pini*, pine plantations have been relatively disease-free. As the eucalypt plantation area is increasing, eucalypt diseases endemic in native forests are spreading into plantations. Examples of these are the problem of *Mycosphaerella* in temperate eucalypts and *Quambalaria pitereka* in sub-tropical species. Similarly, several canker fungi cause severe stem decay in *E. nitens* trees when they are pruned to provide high value logs. There is insufficient information on the impact of these diseases on production. Current work in progress, examining how we can manage them through breeding and silviculture, needs to be strengthened. Threat from diseases, currently offshore, should never be underestimated. Recently CSIRO in partnership with a number of international groups has initiated a forward defence research strategy to gather information on two major threats: pine pitch canker in radiata pine (*Fusarium circinatum*) in California, and guava rust (*Endocronartium harknessii*), which is endemic in Brazil and infects several important eucalypt species.

Insects

The recent arrival of *Essigella* aphid reminds us of the need to be vigilant. It has already cost several million dollars loss in growth of pine in the Green Triangle. For the control of recurring eucalypt pests the industry is reliant on non-specific insecticides, which raise social concern for the environment. Other methods of control, including plant resistance, chemical communication, biological control and biopesticides, are not available and will take time to develop. It is important to invest in research now and be prepared with new options for pest management.

Process-based models

Growth and yield models play a vital role in management decisions, and will continue to do so. However, they have a limited ability to predict and to explore the impact of changing environments on ecosystem process and productivity, and to analyse the impacts of landscape-level process on sustainability. Development of process-based models (Landsberg and Coops 1997; Battaglia *et al*. 2002) and hybrid models (Pinkard *et al*. 2001; Snowdon 2001) has opened new ways of understanding and managing productivity. The models are being used increasingly as management tools and for sensitivity analysis by managers. Continued investments in this area, with close interaction with managers, would greatly improve future decisions and management practices governing on-site evaluation, site and soil-specific silviculture, risk assessment, resource evaluation and sustainability issues at the landscape level.

Remote sensing for forest management

Remote sensing technologies have been in use for land evaluation at a broad scale for many years. Their application to plantation forestry has been limited. Australian research in recent years has focused on capturing, processing and interpreting remotely sensed data in relation to their representation of forest ecosystem structure and processes (Coops *et al*. 1998). Advances in forest growth models mentioned earlier, and the innovations in technology including Hyperspectral Imagery, LIDAR, ECHNIDA™ and access to the NASA satellite-linked Earth Observation System

(EO-1), have opened unprecedented opportunities to apply remotely sensed information for advancing knowledge and for more efficient and potentially cheaper provision of information to management. The experimental studies show great promise for innovations in productivity estimation (and eventually inventory), forest health surveillance, assessment of foliar chemistry, biodiversity and ecological processes, and greenhouse impacts and carbon sequestration. Further development in this area would pay good dividends to the industry.

Precision forestry

Precision forestry is an integrated spatial management system. Site variation in growth has several implications to site-specific management (Turner *et al.* 2001). Forest management is currently guided by broadacre prescriptions although we seek site-specific solutions. Most productivity maps show a mosaic of productivity classes even at small management unit levels, determined by variables including terrain, soils, available water, and pests and diseases. Because of this, the broadacre approach is not efficient. We need to go to a finer scale, make use of the variations for more precise targeting of input to get the best out of every tree, if not every small group of trees (at scales of tens of metres rather than kilometres).

Three streams of innovations make this feasible now: first our scientific understanding of tree growth in relation to site and environment, and advances in process-based models; second, progress in communication and information technologies including GPS, GIS and remote sensing which can locate and report on the condition of the forests; and third, the feedback loop, which can use detailed measurement of field performance (harvested yield) over time to immediately tune the ensuing management action, for example, fertiliser application. Research on precision forestry can integrate these streams and provide a package of capabilities, measures and technologies. Such advances would maximise returns from accumulated knowledge, which is currently underused. Progress in precision forestry will not come simply by wiring up the technologies; significant scientific effort in integration across the streams will be essential.

Low-rainfall forestry

There is abundant discussion and numerous reports on the scope and need for expanding forestry in low-rainfall regions. The reasons include the role of reforestation in combating salinity, potential benefit to biodiversity, carbon sequestration, and the prospects for stimulating regional economies in the long term through forestry business. There are many statistics which report on the potential of the target area for this purpose, especially in Western Australia and the Murray-Darling Basin (MDB). The prospective target areas for plantings of deep-rooted perennial vegetation far exceed the current area of Australian forest plantations.

Commercial plantation forestry is a dryland cropping system, now confined mostly to the 650–850 mm rainfall zone. The general view is that at a lower rainfall level forestry may not be commercially viable, given the prevailing, narrow investment climate. There are also concerns about the environmental tradeoffs, especially in relation to the potential impact of forests on water flows (O'Loughlin and Nambiar 2001). We have little quantitative information on the biophysical issues of tree productivity, and the impact of tree communities on other values in these environments. Experience with the oil mallee program in WA and many observations on growth rates of woodlots in farms (usually poorly managed) in the MDB catchments indicate that productive units of trees can be grown on farms. Mean annual rainfall is often a misleading criterion of available water (within the soil profile or from the water table), which drives growth. Seasonal and annual patterns of rain and evaporation rates are crucial factors.

A nationally coordinated program of genetic evaluation and improvement of key low-rainfall species began only three years ago with the establishment of the Australian Low Rainfall Tree Improvement Group (Harwood and Bush 2002 http://www.rirdc.gov.au/reports/AFT/02-031.pdf). Site and silvicultural system requirements of these lesser-known tree species are not yet well understood. There is general information on the relationship between salinity and tree growth (Lambert and Turner 2000) and there are guidelines for using trees for productive farms and healthy catchments (Stirzaker *et al.* 2002). However, field-based information relating dryland salinity and long-term productivity and on management options for improving production are rare. It is equally important to know the interactions between the new forests and the remnant native vegetation and how they may jointly deliver ecosystem services. None of the process-based growth models now available have been parameterised for low-rainfall species and their environment. Therefore, there is little capacity to simulate and explore the critical constraints to production or ecosystem processes spatially.

The economic imperatives are real but the challenge is to harmonise socially profitable investment linking commercial wood production with environmental credits associated with ecosystem services for the collective good. It is unrealistic to expect an upfront assurance of economic viability of a system when we have invested so little in exploring its potential. Figure 4 is a conceptual model to illustrate how the incremental contributions of production values and environmental credits together can facilitate investment in plantation forestry in low-rainfall zones. In addition to those variables shown in Figure 4, financial and market driven factors would also have a strong impact on the nature and size of potential investments in this venture.

Research and development have a critical role in delivering solutions for each of the potential gains. Apart from the major research efforts required for understanding and solving biophysical constraints, work is also required on how to measure and evaluate the tradeoffs, based on a holistic approach to land use. It is a paradox that many policy initiatives, including market-based instruments designed to promote low-rainfall tree planting, are reluctant to support strategic and applied research essential for systematic and informed action towards this important national goal.

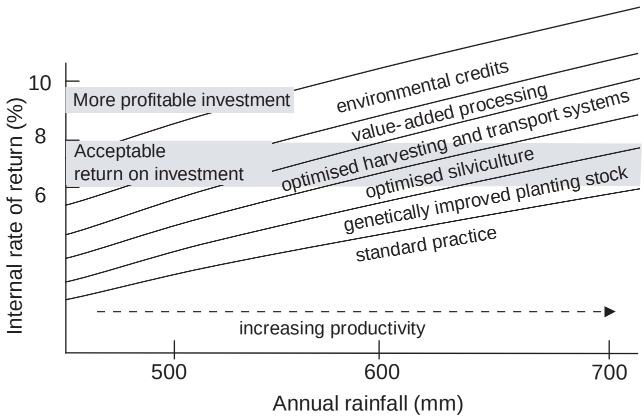

Figure 4. A conceptual model to illustrate how improvements in commercial forestry and environmental credits can together create profitable plantation investments in lower-rainfall environments. Relationships and notional values of IRR are indicative to illustrate trends and aid discussion (C. Harwood, CSIRO, *pers. comm.*, 2002).

Discussion

Sustainability in the broad sense is a balancing act involving both informed and careful management of the resource for production and due care for the environmental values within and beyond the forested area. The characteristics and processes governing individual elements of sustainability (including productivity) change dynamically so that there is seldom an immutable reference point to benchmark the achievement of sustainability. Within the wider framework of a land use system, the goals of plantation forestry are changing, and forestry has an opportunity to provide a wide range of goods and services. The goal of sustainable forestry should not be simply to maintain productivity at the level produced by the previous crop, but to increase the productivity and value of the wood per unit area so that the best use is made of the land set aside for plantations. Maintaining productivity at a low level will be a lost opportunity.

Forest management has improved considerably over the years (Fig. 3), but the gains are taken for granted and our expectations have stepped up to another level. These expectations are intertwined with the goals and values of diverse stakeholders in a complex way. Science-based answers, on their own, cannot resolve all the issues. However, without continued understanding of the process governing the management of plantations, our capacity to resolve problems will be greatly diminished. Such knowledge-based understanding is central for deploying balanced tradeoff arrangements. Unreasonable expectations may destabilise the principles of sustainability in the holistic sense. The setbacks which threatened the orderly development of bluegum industry in recent years are warning signals of unsustainable outcomes.

Assessment and accreditation of sustainability are topics of much discussion as a part of the broader agenda of certification. Australia is a signatory to the Montreal Process, which is yet to produce a set of validated, meaningful and operationally feasible criteria and indicators for assessing sustainability. Some collaborative research involving a number of organisations has been done in Australia on validating and developing selected indicators as proposed in the Montreal Process. The outcomes from those efforts have provided some understanding of how forest management history may or may not relate to prescribed sets of indicators, but the overall results are far from being useable as practical tools. Important decisions are also yet to be made on the scale of management unit to which we may eventually apply the indicators.

A renewed opportunity has risen for forestry as a partial solution to our land and water degradation problems and as a vehicle for delivering environmental services including carbon sequestration. But the associated challenges are immense and require vision and a long-term resolve of great magnitude, along with supportive research and demonstrations at an appropriate level. We must face up to this challenge.

Investments in research are now forced to compete with other demands of immediate management decisions in response to market forces. So does research pay? Most R&D organisations scrutinise the value of their research in terms of benefit–cost ratios, impacts on IRR or business growth. Many such analyses show that investment in research is a wise decision. CSIRO Forestry and Forest Products carried out an impact analysis of a portfolio of five projects and found that the benefit–cost ratio of the portfolio ranged from 22 to 13, depending on the level of uptake (Anon. 1999). A similar analysis commissioned by the CRC for Sustainable Production Forestry (Anon. 2002) showed that the net benefits of six individual projects ranged from $1.8 million to $190.9 million to its industry partners with a corresponding benefit–cost ratio ranging from 5 to 137. The net benefits to Australia from investments in research are much more than can be measured in a narrow economic analysis.

We should recognise that the benefits we now reap from improved management and investment decisions are the product of research decisions made and the work fostered, sometimes over decades. Advances in sustainable plantation forest management are not characterised by dramatic and quantum leaps. Progress is made through gradual, incremental and enduring steps. Such advancements require sustained, long-term research effort.

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References

Anon. (1999) Benefits from CSIRO research for the Forestry, Wood and Paper Industries Sector. CSIRO Internal Report, Canberra, 82 pp.

Anon. (2002) Economic evaluation of Research and Development Portfolio. CRC Sustainable Production Forestry Internal Report. Centre for International Economics, Canberra and Sydney, 53 pp.

Battaglia, M., Mummery, D. and Smith, A. (2002) Economic analysis of site survey and productivity modelling for the selection of plantation areas. *Forest Ecology and Management* **162,** 185–195.

Boardman, R. (1988) Living on the edge: the development of silviculture in South Australian pine plantations. *Australian Forestry* **51,** 135–156.

Carlyle, J.C. and Nambiar, E.K.S. (2001) Relationships between net nitrogen mineralization, properties of the forest floor and mineral soil, and wood production in *Pinus radiata* plantations. *Canadian Journal of Forest Research* **31,** 889–898.

Coops, N.C., Waring, R.H. and Landsberg, J.J. (1998) Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite derived estimates of canopy photosynthetic capacity. *Forest Ecology and Management* **104,** 113–127.

Harwood, C. and Bush, D. (eds) (2002) *Breeding Trees for the Low Rainfall Regions of Southern Australia.* Rural Industries Research and Development Corporation (RIRDC) Publication No. 02/031, Canberra, 23 pp.

Lambert, M. and Turner, J. (2000) *Commercial Forest Plantations on Saline Lands*. CSIRO Publishing, Australia.

Landsberg, J.J. and Coops, N.C. (1997) Modelling forest productivity across large areas in long periods. *Natural Resource Modelling* **12,** 1–18.

Nambiar, E.K.S. (1996) Sustained productivity of forests is a continuing challenge to soil science. *Soil Science Society of America Journal* **60,** 1629–1642.

Nambiar, E.K.S. (1999) Productivity and sustainability of plantation forests. *Bosque* **20,** 9–21.

Nambiar, E.K.S. and Brown, A.G. (1997) Towards sustained productivity of tropical plantations: science and practice. In: Nambiar, E.K.S. and Brown, A.G. (eds) *Management of Soil Nutrients and Water in Tropical Plantation Forests.* Australian Centre for International Agriculture Research (ACIAR). Monograph No. 43, Canberra, Australia, pp. 527–557.

Nambiar, E.K.S. and Brown, A.G. (eds) (2001) *Plantations, Farm Forestry and Water*. Proceedings of a National Workshop, Melbourne July 2000. A report for the Joint Venture Agroforestry Program. RIRDC Publication No. 01/20, Canberra.

Nikles, D.G. (1996) The first 50 years of the evolution of forest tree improvement in Queensland. In: Dieters, M.J., Matheson, A.C., Nikles, D.G., Harwood, C.E. and Walker, S.M. (eds) *Tree Improvement for Sustainable Tropical Forestry.* Proceedings QFRI-IUFRO Conference, Queensland, pp. 51–64.

O'Loughlin, E. and Nambiar, E.K.S. (2001) *Plantations, Farm Forestry and Water: A Discussion Paper.* Report prepared for the Joint Venture Agroforestry Program. RIRDC Publication No. 01/137.

Pinkard, E.A., Battaglia, M., Beadle, C.L. and Sands, P.J. (2001) Using hybrid models to develop silvicultural prescriptions for *Eucalyptus nitens*. *Forest Ecology and Management* **154,** 337–345.

Powell, M.B. and Nikles, D.G. (1996) Performance of *Pinus elliottii* var. *elliottii* and *P. caribaea* var. *hondurensis*, and their F_1, F_2 and backcross hybrids across a range of sites in Queensland. In: Dieters, M.J., Matheson, A.C., Nikles, D.G., Harwood, C.E. and Walker, S.M. (eds) *Tree Improvement for Sustainable Tropical Forestry.* Proceedings QFRI-IUFRO Conference, Queensland, pp. 351–354.

Snowdon, P. (2001) Short-term prediction of growth of *Pinus radiata* with models incorporating indices of annual climatic variation. *Forest Ecology and Management* **152,** 1–11.

Stirzaker, R., Vertessy, R. and Sarre, A. (2002) *Trees, Water and Salt: An Australian Guide to Using Trees for Healthy Catchments and Productive Farms*. Joint Venture Agroforestry Program, RIRDC Publication No.01/086, Canberra, Australia, 159 pp.

Turner, J., Lambert, M.J., Hopmans, P. and McGrath, T. (2001) Site variation in *Pinus radiata* plantations and implications for site specific management. *New Forests* **21,** 249–282.

Woods, R.V. (1990–91) Second rotation decline in *P. radiata* plantations in South Australia has been corrected. *Water, Air and Soil Pollution* **54,** 607–619.