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Productivity and sustainability of plantation forests*

Productividad y sustentabilidad de las plantaciones forestales

E.K. SADANANDAN NAMBIAR

CSIRO Forestry and Forest Products, PO Box E4008, Kingston, ACT 2604, Australia.

RESUMEN

El autor identifica una serie de objetivos generales en las plantaciones forestales y discute algunos de sus aspectos relacionados con: el creciente papel de ellas en la obtención de beneficios económicos y ambientales, las tendencias de su productividad a largo plazo, los conflictos que causan por las demanda y necesidades de suelo y la estimación de su sustentabilidad.

Lo medular en la sustentabilidad de plantaciones es la producción rentable y permanente de madera cuidando simultáneamente el medio ambiente. A pesar de la creciente preocupación, en la mitad de los años 60, sobre la disminución del rendimiento de las plantaciones forestales, existen claras evidencias que demuestran que en las zonas templadas frías y cálidas del mundo la productividad de las plantaciones ha aumentado durante las últimas décadas, lo que constituye un punto a favor de la ciencia y el manejo forestal. Al evaluar la sustentabilidad de la productividad se debe reconocer que no existe un punto de referencia inamovible al cual se pueda recurrir para calibrarla, es decir, los índices de productividad sólo pueden dar una información puntual en el tiempo. Los conocimientos básicos para lograr una mejor evaluación y satisfacción de las expectativas de sustentabilidad, con las correspondientes obligaciones que ello implica, requieren de una actualización permanente del conocimiento, a través de su aplicación en terreno y ajuste permanente.

En la medida en que las plantaciones forestales se expanden, entran en conflicto con otros usos de la tierra. Un ejemplo de lo anterior es el impacto de las plantaciones sobre el recurso agua, también requerido para otros usos. La solución a estos conflictos requiere de investigación y estrategias de comunicación para incorporar a la comunidad en forma constructiva en esta problemática.

La sustentabilidad no sólo es de importancia comercial, es también una obligación nacional e internacional. Nociones simplistas de criterios e indicadores para lograr la sustentabilidad sólo aportan poco. Sin embargo, la utilización de conocimientos científicos, ponderando adecuadamente los objetivos medulares de las plantaciones forestales, permitirá el desarrollo de oportunidades crecientes para la industria basada en ellas.

Palabras claves: productividad, sustentabilidad, plantaciones.

ABSTRACT

I have identified a set of generic goals for plantation forestry and discussed some of their aspects in relation to the expanding role of plantation forests for economic and environmental benefits, the trends in long-term productivity, conflicting demands and needs in land use values, and assessment of sustainability.

Profitable and sustained wood production with environmental care is at the heart of sustainable plantation forestry. Despite the rising concern, in the mid 1960s, about the decline in yield of plantation forests, there is a substantial amount of evidence to show that in temperate and warm temperate areas of the world, plantation productivity has increased during the last decades; a credit to forest science and management. In evaluating sustained productivity we need to recognise that there is no immutable reference point against which productivity can be bench-marked, and indices of productivity may only provide a snap-shot in time. The base knowledge required to achieve this and to accommodate the inevitable and diverse obligations and expectations of sustainability requires continuous updating of this knowledge through its application in the field, as well as appropriate feedback.

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As plantation forestry expands, it comes into conflict with other land-use values. A striking example is the widespread concern about the impact of plantations on water resources available for other purposes. The solution of these conflicts requires sound research results and communication strategies to constructively engage the community.
Sustainability is not only important commercially, it is a national and international obligation. Simplistic notions of criteria and indicators for assessing sustainability may achieve little, but scientifically based assessments with appropriate weighting given to the core goals of plantation forestry could further advance the growing opportunities of plantation based forest industries.

Key words: productivity, sustainability, plantations.

INTRODUCTION

Plantation forestry is steadily expanding around the world, under diverse bio-physical, social and economic environments, and is providing a range of products and services. Plantations have increasingly become private business enterprises for economic benefits, whether managed by small farmers or multinational corporations. Native forests are still cleared to establish plantation forests in some countries, but this practice is rapidly declining globally. In many countries such forest conversion is now heavily regulated or outlawed. Thus plantation forestry, with some exceptions, is substantially a land use system based either on successive rotation of plantations or on 'new forests' established on land often degraded by other activities including agriculture. Plantation forests are not natural assets in the same sense as native forests; they are assets deliberately grown, often described as tree farms, for one or more specific purpose.

Plantation forestry has a commercial focus. However, management goals for plantations are diverse and strongly interactive with economic, environmental and social values. Therefore their links in the broader concept of sustainable development evoke many expectations and conflicting values. It is important to have clearly stated goals relevant to national, regional and local contexts to achieve sustainability in a practical sense, as well as for the ongoing realisation of the full potential of plantation forestry. A core set of generic goals include (Nambiar 1996a,b):

- to ensure that the trend in plantation productivity is non-declining over successive harvests;
- to protect and if possible enhance the quality of soil and water in the plantation environment;
- to promote innovation and profit of growing and utilising wood for the business;
- to improve the economic and social benefits to the community.

There may be other goals, for example, land care and bio-diversity values that may be accommodated or even enhanced depending on the ecosystem that is being managed. The emphasis on any one or set of goals is a matter of local decision. Although, in reality we can rarely give equal weighting to all goals, it is not acceptable to single-mindedly pursue any one goal (including a commercial goal) while disregarding other values.

In this paper I would like to discuss some aspects of these goals. I wish to focus on the expanding role of plantation forests; trends in long-term productivity; interaction between productivity and landscape values; and, how sustainability may be assessed. The continued and sustained growth of plantation forestry is an ongoing challenge for all of us. It can only be met through establishing partnerships between forest scientists, managers, policy makers and the community.

EXPANDING ROLE OF PLANTATION FORESTS

Increased wood production. Historically many countries have planted forests, mostly of exotic species, to supplement wood obtained from native forests for the local timber industry. In many cases, this has not been sufficient to avoid a mismatch between supply and demand. Estimates of wood demand vary greatly for a variety of reasons. According to Apsey and Reed (1995), the predicted global supply gap in 2010 will be 550 million m^3, increasing to 675 million m^3 by 2020. The European Forest Institute (EFI Annual Report 1996) projected that by the year 2050, 'with a higher GDP constant price' scenario, world consumption will reach about 3 billion m^3 per year and that under a 'lower GDP, 0.5 % per year price increase' it will reach about 2 billion m^3 per year. Fuelwood shortage is endemic in many developing countries. If the rate of deforestation for fuel wood continues at the current pace until the year 2020, the loss of about 23% of the forest cover in the world today could occur (Apsey and Reed 1995), exacerbating the shortage of wood and ecological degradation. There are great disparities in wood consumption between poor and rich countries. For example, according to FAO figures for 1993, global timber consumption ranges from (a mere) 5 m^3 to 600 m^3 per 1000 people. Regardless of the variations in estimates of consumption and production, all information leads to the conclusion that a serious wood deficit will occur in the future.

Such increasing demands for industrial wood, fuelwood and charcoal cannot be met by native forests. Sustainably managed plantation forests offer a great opportunity and, the only feasible means, for meeting future wood demand (eg: Shepherd 1993, Brown *et al.* 1997). Kuusipolo (1996) examined the sustainability and rehabilitation of forestry in Indonesia and suggested that the conversion of 1% of *imperata* grassland back to a productive plantation forest state, with the help of fast-growing trees, would be enough to provide the wood supply for a 500 000 ton pulp mill, and consequently, would save approximately an equal area of natural forest from maximal exploitation. Indonesia has embarked on large-scale development of fast-growing plantations of *Acacia* and *Eucalyptus* and plans to progressively shift its wood consumption requirements from native forest harvest to plantation-grown wood. The wood products industry in India argues that India has some 130 million ha of degraded forest land, and if they are allowed to grow plantations in some 1% of this land, the current 'raw material crises' in India can be met. They also hold that they can do so with due environmental and social care (India Report, March 1996).

In several countries (e.g. : Brazil, Chile and New Zealand), plantation forestry already has a growing role in economy and employment. In New Zealand, the forestry industry now contributes 6% of GDP (O'Loughlin 1995), and with planned expansion, it is poised to become the largest export earner. Ambitious programs to expand plantations and farm forestry are being promoted in countries as diverse as Australia, China, India and Uruguay. Australia has embarked upon a national vision - Plantations for Australia: the 2020 Vision - which sets the stage for trebling the area under plantations by the year 2020. At a global level, areas under plantation forestry doubled from 85 million ha in 1980 to 180 million ha in 1995. By the year 2010 this figure is expected to double again (FAO 1997). While the scope appears promising for large-scale development of plantation forestry in the tropics, their long-term success will depend on sound land use decisions and sustainable management (Nambiar and Brown 1997a).

Environmental benefits. Although plantations are mainly intended to produce wood on a commercial basis there is an increasing recognition of the value of plantations as a form of land use to enhance environmental benefits (Nambiar 1997, Kile *et al.* 1998).

Mitigation of land degradation. Farm forestry plantings are being promoted for the dual purpose of growing wood and improving soil and water quality of agriculturally degraded land. A successful example is the integrated program to combat wide spread soil-water salinity in Western Australia (Shea and Hewett 1997). Tree planting can also improve the physical environment and biodiversity in farms. For Australia, the estimated non-market benefits from trebling its plantation resource, primarily through farm forestry, are considerable (CIE 1997). These include a 60% increase in employment in some regions, a halt in farm decline with up to 20% increase in income, savings up to $85 ha^{-1} by repairing soil degradation and a contribution to carbon sequestration equivalent to carbon tax offsets of $13 ha^{-1}. Although these are only forward estimates, they do indicate the opportunities that are ahead for Australia.

Climate change. The rising CO_2 levels and predicted changes in climate are major global issues. The potential of plantations to sequester atmospheric carbon and thus contribute to management of this issue is much debated. Estimates of the amount of carbon that can be sequestrated in this way, in comparison with the amount that is emitted and the overall carbon budget vary considerably, for any geographical location. Because CO_2 will be both sequestered (depending on growth rates) and released (by decomposition and burning) during the life cycles of plantations, the role of plantations as a carbon 'sinks' and their environmental impact depends upon the dynamics of plantation establishment, management and utilisation. For example in 1990 in New Zealand, the fossil fuel - carbon emissions totalled 8 Mt yr^{-1} and the rate of carbon sequestered by forests was 3.5 Mt yr^{-1}, or about 44% of the emission. In comparison the emission in USA was 1300 Mt yr^{-1} against a forest sequestration of 80 Mt yr^{-1}, or only 6% of the emission (Brown 1995). By comparison, a sustained plantation development program of 1.6 million ha over 40 years is estimated to make a contribution of about 10% in reducing Australia's net CO_2 emissions (Barson and Gifford 1990). Plantation forests can be important sinks in some cases (Apps and Price 1996) and some analyses show them among the relatively low cost options for carbon sequestration (Sedjo 1996).

The ideas of carbon tax and carbon credits are being canvassed as a way of apportioning responsibility to those who contribute to emissions or promote sequestration as a part of an overall strategy to deal with carbon emission. The idea of 'carbon credits' requires well defined actions by industry to increase carbon sequestration through increasing plantation forests, and these would be accounted as 'offsetting credits' against the emission caused by other industrial economic activities. This idea has captured the attention of non-forest industries based on fossil fuel, and may lead to new opportunities for plantation forestry.

Biodiversity. Recent research has provided new possibilities for restoring native species richness on degraded land by first planting monoculture of exotic species selected to match site conditions. In turn, they foster an environment conducive to the regeneration of a variety of native species (Parrotta 1992, Lugo 1996). Recent results from commercially managed hoop pine plantations in Queensland (Australia) show that numerous native species have re-established as understorey (Co-operative Research Centre for Tropical Ecology, Annual report 1996). These results seem a paradox, but, along with research from elsewhere they question the validity of the assertion (sometimes) made that plantations are 'biological deserts'. Thus industrial plantations, farm forests, wood lots for fuel, and plantations established primarily for environmental protection (land rehabilitation, biodiversity rejuvenation, or catchment protection) are all inalienable links in a continuum of sustainable land use. Several types of plantation development to suit one or more land use objectives are possible. Plantations, if managed well are highly productive and can be a major source of wood production in relatively small areas. The primary role of plantations regardless of the size of the investment, is *wood production with environmental care.*

PRODUCTIVITY IMPROVEMENT IN THE LONG-TERM

A central element of sustainability is historical knowledge, and management of long-term productivity. Site productivity is represented and measured in a variety of ways (e.g.: net primary production, above ground biomass, merchantable stem wood) and there is a plethora of management and research indices used to describe potential and realised production: site index, site quality, site potential, site carrying capacity and others. An analysis of the relative merits of these indices is not within the scope of this paper.

In plantation forestry, few site characteristics have been monitored over the long-term. Even when some changes in long-term trends are found, it is difficult, if not impossible, to explain such trends in terms of biophysical processes and their interactions. Nevertheless, it is important to review the trends in production of some ecosystems, where data are available. These can help us to relate to what is known about the basic principles that govern productivity.

Figure 1 shows the change in productivity of *Pinus radiata* achieved by application of improved management practices (improved planting stock and site management) by a private forest owner in Australia (Leishout *et al.* 1996). The authors used volume growth of all plantations established before 1971 as the unimproved base line for compiling these data. The lack of balanced 'control plots' was partly compensated by stratification of data by soil types, and the availability of over 10,000 plots systematically positioned throughout the estates. Results show a big and continuing improvement across all 14 soil types within the three major soil groups, with average increases of 77% on uniform sand, 55% on Duplex soil and 53% on clay loam. Leishout and colleagues examined the realised gain since 1988, and point out that using pre-1971 volume growth as a base line, the gain was 49% in 1988, 51% in 1993 and 63% in 1995 (Fig. 2), showing a steady upward trend. Furthermore, plantings until 1971 (base line) were entirely on first rotation sites, whereas between 1980-84, 57-78% of the area planted was second rotation sites (2R - pine after pine). The progressive increase in MAI leading to 66% by the 1980-84 planting over the 1971 base line shows how improved management has increased productivity of successive crops.

Figure 2 shows the pattern of volume growth of plantations established between 1950 to 1984. The annual fluctuations are caused by proportional planting across various soil types and seasonal variations. The overall trend is positive increasing from about 7 $m^3 ha^{-1} yr^{-1}$ to 15 $m^3 ha^{-1} yr^{-1}$. The substantial improvement since the late 1970s has been somewhat dampened by a large reduction in the early 1980s following a severe drought period.

Plantations of *P. radiata* established in the south-east of South Australia and western Victoria contribute with a significant proportion of the wood produced in Australia. Local industry is entirely dependent on wood grown locally, on second and third rotation sites. Long-term research and its systematic application has produced profitable silvicultural options to not only to maintain yield but also to enhance it over extensive areas (Boardman 1988). Forestry (South Australia), 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) and compared the results with yield assessments made in earlier years. The assessment techniques were based on well established inventory methods which allowed reliable predictions of yield over a full rotation, from measurements at age 10 years, if stands were managed according to prescribed thinning regimes. The result of that evaluation is shown in Figure 3. To simplify the presentation, I have aggregated the data into three groups to indicate high, medium and low productivity classes. The results show that in the early 1960s, about 70% of the total plantation area was in the range SQ V-VI (MAI 18 to 13 $m^3 ha^{-1} yr^{-1}$ at the maximum MAI age of 36 to 37 years). The growth trends of subsequent plantations, planted in 1984 (measured in 1994) on predominantly second- and third-rotation sites have provided a basis for upgrading many sites to SQ I-III (MAI 33 to 25 $m^3 ha^{-1} yr^{-1}$ at the maximum MAI age of 29 to 32 years). At present, the organisation has less than 10% of their total estate classified in the low productivity class SQ V-VI. A comparison of productivity of first- and second-rotation stands within the same sites at the compartment level mirrors this pattern of site quality upgrading (Nambiar 1996b). This is a remarkable long-term improvement in site productivity.

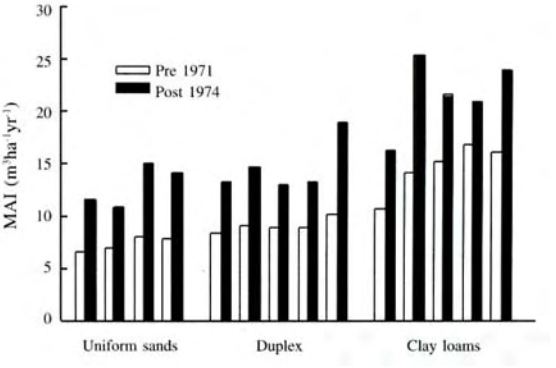

Figure 1. Realised gains in Mean Annual Increments (MAI) measured at age 11 years for *Pinus radiata* from improvements in silviculture and tree breeding since early 1970's. Sites in Gippsland, Australia. Individual histograms within the major soil groups represent different soil types (Leishout *et al.* 1996).

Aumentos obtenidos en el incremento medio anual de *Pinus radiata* a los 11 años de edad, con medidas de mejoramiento silviculturales y genéticos, al principio de los años 70, en sitios de Gippsland, Australia. Los histogramas individuales, dentro de los grupos de suelos indicados, representan diferentes tipos de suelos (Leishout *et al.* 1996).

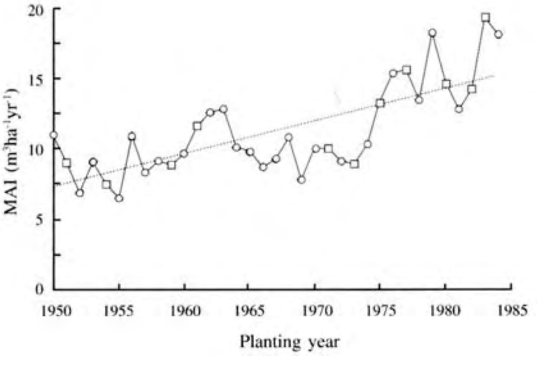

Figure 2. Long-term trends in MAI across many sites, soil types and planting year spanning 34 years. MAI was measured at age 11 years, the last set of measurement being in 1995 (planted in 1984) (Leishout *et al.* 1996).

Tendencia de largo plazo del IMA, en representación de muchos sitios, tipos de suelo y años de plantación para un período de 34 años. El IMA fue medido en plantaciones de 11 años y el último set de mediciones fue efectuado en 1995 (plantación de 1984) (Leishout *et al.* 1996).

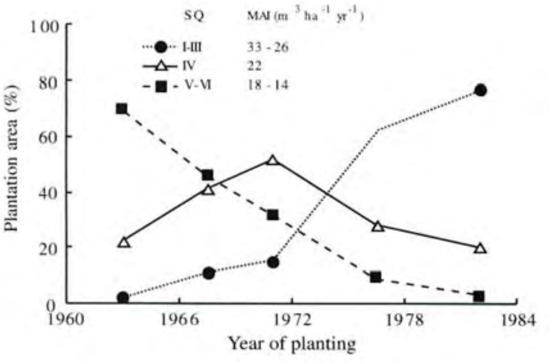

Figure 3. Long-term trends in the area classified in various Site Quality classes of second- and third-rotation plantations of *Pinus radiata* on podzolised sandy soils in South Australia. (Forestry (S. Australia), 1995, personal communication).

Tendencias de largo plazo de la superficie ocupada por clases de sitio para *Pinus radiata,* en segunda y tercera rotación, sobre suelos arenosos podsolizados en el Sur de Australia (Forestry (S. Australia), 1995, comunicación personal.

With scientifically based management, ongoing overall improvement in wood yield from plantations are being achieved across a range of soil and environmental conditions in Australia (Figs. 1, 2 and 3) (Nambiar 1995, Borschmann 1995, Long 1997). Gonçalves *et al.* (1997) discussed several soil and stand management issues critical for achieving sustained productivity of short-rotation, fast-growing eucalyptus plantations in Brazil. An inventory of productivity of plantations in Brazil showed that productivity increased steadily by 40% in wood yield, and by 75% in pulp yield from 1980 to 1995 (see Nambiar 1997 based on a report by ABECEL 1995).

Assessment of long-term realised gains in wood production over broad areas is not easy for several reasons worth briefly examining here. First, scientific and technical improvements and their application in forestry have seldom been characterised by spectacular jumps (unlike advances in the use of drugs for disease control); improvements are incremental, and trends are influenced by many biophysical variations and investment decisions. Second, productivity during one growth rotation alone can be dramatically influenced by weather, especially distribution and quantity of rainfall. Third, since it is difficult to include strict biological controls against which continuous improvements can be measured in space and time, a large and long-term inventory system with sound stratification to represent landscape, soil and silvicultural variations is necessary to obtain reliable measures of realised gain. Furthermore, changes in yield measured by various management inputs (e.g.: potential benefits of tree breeding, growth response to silviculture etc.) are from small plots under conditions designed to maximise the response to applied treatments and often lack the reality of the large-scale operational plantations. This has required the careful adjustment of gains from research plots downward, to ensure representation over forest management units (Leishout *et al.* 1996). Despite these constraints, systematically collected, adequately stratified, long-term growth data is invaluable not only for understanding long-term changes in productivity and sustainability in a true sense but also for making critical management decisions. The overall global trend indicates that productivity of intensively managed plantation forests is increasing (Nambiar 1997).

KNOWLEDGE BASE AND SILVICULTURAL DECISIONS FOR MANAGING PRODUCTIVITY

Site-stand management. The productivity of successive crops over (the) a long-term can be influenced positively or negatively, by site and stand management operations at any stage during the rotation. However, in general, the most intensive impacts on the soil and site environment occur during the inter-rotation management period through operations which include harvesting, site preparation, vegetation management and other early silvicultural practices. During this period sites may be heavily disturbed and exposed to degradation processes (e.g. soil erosion, loss of organic matter and nutrients through fire, leaching and displacements) which can also cause adverse off-site impacts (e.g. pollution of streams). Management strategies based on practices including genetically improved planting stock, site preparation practices that conserve site resources and improve availability of water and nutrients, and control of competition are critical elements for increasing productivity. There is a substantial body of information on the process associated with inter-rotation management practices, and there are many technological solutions that can be adapted to suite site-specific conditions and production goals (e.g. Boardman 1988, Nambiar and Sands 1993, Beets *et al.* *1994,* Nambiar 1996b, Fife and Nambiar 1997, Gonçalves *et al.* 1997).

There are indeed many more challenges to overcome. A comprehensive review of those issues are not within the scope of this paper. However, let me illustrate two cases especially related to *P. radiata* silviculture as examples. In Australia, *P. radiata* is grown under winter rainfall - dry summer environments commonly leading to large water deficit. Growth of stands is predominantly influenced by available water (Fig. 2). For making sound investments in silviculture, managers need tools to predict the nature and extent of growth response obtainable for a given management practice. For example, we do know that growth response to the application of fertilisers to late-age stands is dependent upon several soil (e.g. rates of mineralisation, available soil water), and stand-eco-physiological attributes including LAI (e.g. Carlyle 1995, in press). Interaction between nutrients and water is often the key to productivity (Nambiar 1990/91, Kimmins 1994, Carlyle in press).

The nature and degree of the influence of climatic factors on production can be examined through process-based models. Snowdon *et al.* (in press) used a process-based model, BIOMASS, to estimate variation in photosynthesis by (in) several stands. They used a simplified non-varying canopy structure, a fixed LAI value and crown configuration, physiological parameter for *P. radiata* and soil moisture characteristics appropriate to the sites (Fig. 4). Simulations were carried out using daily data for rainfall, maximum and minimum temperature. The results showed that the 48-year average for the climate index varied from 17.3 and 29.9 C t ha^{-1}. On a wet site (long-term annual rainfall, 1120 mm) annual variation was about 15 t C ha^{-1},and on a dry site (long-term annual rainfall, 646 mm) it was about 9 t C ha^{-1}. These large variations in photosynthesis would lead to equally large variation in growth between sites and growing seasons. Estimates and prediction of yield usually do not take into account the endemic vagaries of climatic factors and therefore can suffer from significant bias and inaccuracies depending upon the nature of the climatic variation itself (Snowdon *et al.* in press). Because of this, short-term yield forecasts based on empirical growth models and long-term average rainfall for a region, a common practice in most yield estimates, are prone to a high degree of bias and inaccuracy (Snowdon *et al.* in press).

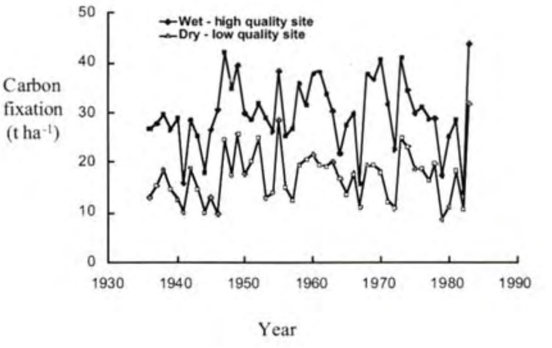

Figure 4. Variation in annual photosynthetic carbon fixation over long-term, estimated by BIOMASS model for two sites with contrasting Site Index in Australian Capital Territory (Snowdon *et al.* in press).
Variación anual de la fijación fotosintética de carbono en el largo plazo, estimada por el modelo BIOMASS, para dos sitios con índices de sitio diferentes en el territorio de la capital de Australia (Snowdon *et al.* en prensa).

Because mid-rotation fertiliser application is an economically attractive proposition for increasing wood yield in a relatively short time (5-10 years), efficient tools to predict the probability, size and longevity of the growth response to fertiliser application at a management unit level is a very attractive area for research. Figure 5 shows the results of a survey of mid-rotation fertiliser experiments on *P. radiata* in Australia and New Zealand. The probability and size of the response depends on the element applied and many site and stand characteristics. The proportion of experiments which give zero response are common if only N or P alone are applied. The size and probability of response increases when N and P are applied together (Fig. 5). If growth is simultaneously limited by N and P, application of one element alone is likely to be a waste of money. In large-scale operations, wide variations in growth response will lead to unpredictable outcomes and return from investments. Simple, traditional foliar analysis has been useful in the past to identify areas of gross nutrient deficiency. As the overall quality of site-stand management has improved (Fig. 2 and 3), marginal deficiencies are more common than acute ones. In a number of circumstances the availability of water would have an overriding influence on the size and longevity of response (Nambiar 1990/91). The above examples illustrate that despite the fact that there are improved technologies available for increasing production, more opportunities await for further improvements by linking

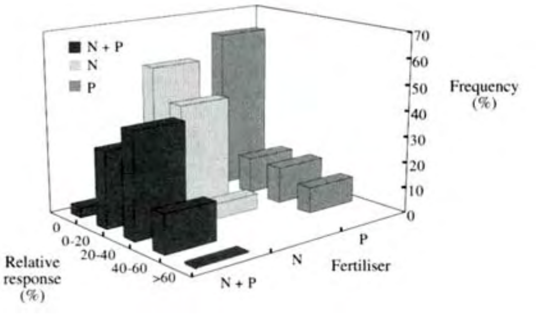

Figure 5. Relative basal area response to phosphorus, nitrogen and phosphorus + nitrogen measured in a range of experiments in New Zealand and Australia (Carlyle, personal communication).

Respuesta del área basal a fertilizaciones de fósforo, nitrógeno y nitrógeno + fósforo, expresada en porcentaje, en vanos experimentos de Nueva Zelanda y Australia (Carlyle, comunicación personal).

new information on soil based parameters and stand physiology. The development of progressive management practices is dependent on two critical factors: research directed at the fundamental factors which determine productivity, and an organisation's ability and determination to implement research findings.

Genetic improvements for high productivity. Continuous improvements in the genetic make up of planting stock have been an integral part of the advances in plantation forestry. Tree improvement programs designed to support this are based on inter-related activities that include matching genotypes to a site, recurrent cycles of breeding (including hybridisation) to maximise the combination of genes affecting economically important traits (growth of wood quality, resistance to pests and diseases) and developing propagation methods for large-scale production of planting stock of elite genotypes.

Common aims of tree breeding strategies are: (Nambiar 1996a) (1) to develop genotypes (breeds) that have high harvest index (measured as stem volume) and produce wood of the quality required for manufacturing specific products, and (2) to reduce the interval between generations so that the genetic gain per unit time can be maximised and planting stock upgraded at each (shorter) harvesting cycle. It is also concerned with reducing the cost of breeding and propagation. Improvements in genetic gain over successive generations depend upon the quality and precision with which tree breeding programs are implemented. The need to maintain the balance between these commercial objectives, ecological risks and sustainability have been discussed elsewhere (Nambiar 1996a).

The realised and expected gam in stem growth (volume) of *P. radiata* by using seeds from first generation seed orchards range from 15 to 30% over unimproved seeds (Matheson *et al.* 1986, Johnson 1991). Advanced-generation breeding strategies involving control-pollinated breeding populations and clone propagation are estimated to provide further genetic advantage (based on estimates of realised breeding values) ranging from 14 to 20% (in basal area) over the previous generation (White *et al,* in press). The Southern Tree Breeding Association (STBA), a Co-operative of plantation growers in Australia, estimated that the genetic gain achieved by open-pollinated and control-pollinated seed options would increase from about 12% obtained in 1980 to 26 and 38%, respectively, by year 2000 (STBA 1997).

Most analyses of genetic gam are based on 'estimated gain'; measured values of real gain obtained from broad, operational plantings are rare. In most breeding programs, the selection and testing of genotypes for economic traits are commonly carried out under conditions where the inherent constraints (stress) at a site are removed or minimised by soil and stand management practices. There are many impediments to capture the 'estimated' genetic gain in an operational scale and it is important to be cautious and conservative when projecting the benefits of breeding research (Haines 1995, Nambiar 1996a).

Tree breeding is not a panacea, and use of genetically improved planting stock without appropriate site-soil management will mostly lead to little (small) benefits. It should also be noted that, in general, regardless of the breeding strategy adopted, higher productivity requires higher levels of resource inputs and intensity of management. The amount of water transpired by *P. radiata* is directly proportional to stem size (Teskey and Sheriff 1996) and amounts of nutrients removed in logs is directly proportional to stem volume regardless of family variation in growth (Nambiar 1996a). Productivity of most plantation areas is limited by more than one site resource. Furthermore, the genetic correlation between traits may be positive or negative, and from a practical point

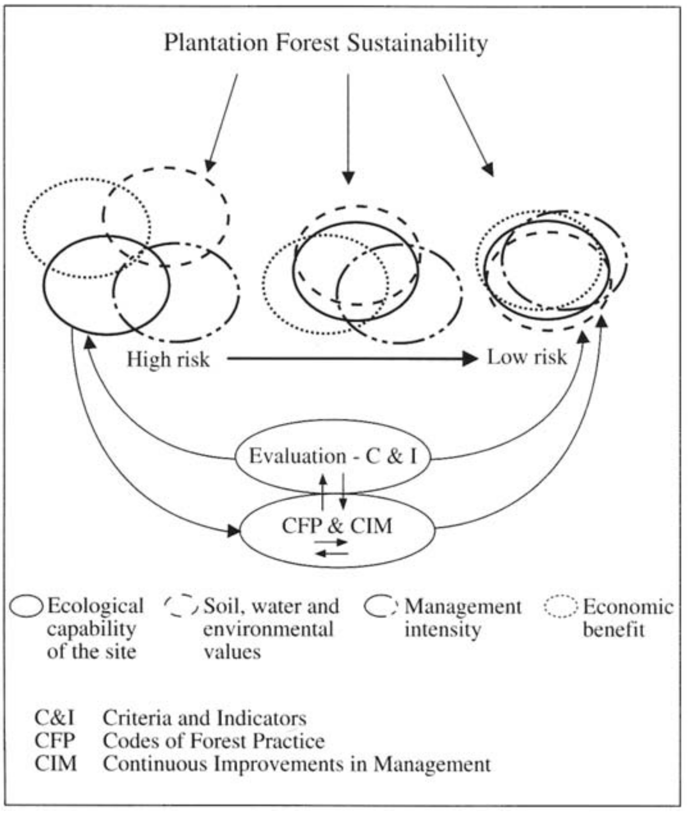

Figure 6. Interactive variables and their alignment in relation to risks, assessment of sustainability (Criteria and Indicators) and continuous improvement in management (Nambiar 1996, Nambiar 1997).
Variables interactivas y su ordenamiento en relación a riesgos, a la sustentabilidad (criterios e indicadores) y al continuo mejoramiento del manejo (Nambiar 1996, Nambiar 1997).

of view the addition of every trait to breeding objectives adds complexity and cost to breeding programs and their application.

I have not addressed the issue of log and wood quality, which has a great impact on profitability and increasingly, on competitiveness in the market. Research on tree breeding, nutrient management and stand management offers opportunities for improving quality of wood and its suitability for specific end products.

SUSTAINABILITY AND ITS ASSESSMENT

Interacting variables. The nature of investments in and ownership of plantations, their intended use, and the strong commercial focus of managers will impact on management practices in many ways. Expectations of production are high, - a policy of sustaining production at a static level is a lost opportunity-, and in commercial forestry, managers are not simply satisfied by maintaining yield. The balance between environmental and production values is accounted for in terms of unit cost of wood because, compliance with many environmental principles is seen as an added cost on production. Nevertheless, plantation forestry has to be, for its long-term future, in harmony with the societal needs, awareness and expectations of sustainable development (Nambiar and Brown 1997b).

The risks to plantations and prospects for their sustainability can be examined in terms of the degree of alignment of a set of core interactive variables (Nambiar and Brown 1997b, Fig. 6). The ecological capacity of plantations is bound by inherent soil and biophysical constraints (especially available water), the genetic potential of the species, and its ecological match with the site. Management systems which exceed these bounds can lead to productivity loss and failed investments. The intensity of management applied to a site and its impact on production, will change as our knowledge, expected outcome, and commercial realities change (Fig. 6). Economic efficiency is dependent on cost of production at the site and at the mill, combined with product development and market opportunities. The enhancement of the productive capacity of the soil, wherever possible, is a good fundamental basis for sustainability. If soil properties are sustained through judicious management *in situ* adverse off-site impacts can be minimised.

Impacts on water resources. A striking example of the way plantation forestry comes into conflict with the multiple use of land, can be seen in the concern about the threat of expanding plantations that would use up the available water for other purposes. This concern has led to the opposition to or negative perceptions of plantation forestry in several countries.

South Africa has a forest industry providing many economic benefits for society based plantations of exotic species. Yet, the expansion of plantations has been severely restricted since the 1970s. The predicted demands for wood and water are expected to increase in 10-20 years (Dye 1996), a sensitive and delicate issue in a country where the amount of available water per capita is very low. Apart from the social issues related to the close link between land tenure and access to water for the population, there are two important biophysical considerations: (i) commercial forestry which occupies about 2.5% of the land area, is located over the same limited area that receives the best rainfall (>850 mm per year) and (ii) plantations established on catchments which were under native vegetation have reduced the amount of water that flows into the river system in an amount equivalent to 100-200 mm yr^{-1} of rainfall. On a broad scale, this has caused an overall reduction of about 30% in available water (Scholes *et al.* 1995). The impact of forestry on stream How at the catchment level can be severe, depending on the hydrological process in the catchment, plantation species, their growth rates, rotation length and management systems (Table 1). Apart from water, other considerations of sustainability including plantation scale and location, biodiversity, soil values, aesthetic values, economic and social imperatives including labour, and the long-term sustainability of plantation forestry are topics of serious discussion and analysis in South Africa (eg: Scholes *et al.* 1995, Versfeld 1996, Olbrich *et al.* 1997).

The profound questions to be dealt with include equity in access to water, based on fundamental principles enshrined in the constitution, and criteria for costing the water as a national resource, based on a balanced evaluation of its use for national benefit. The various options being considered will have major impact on the forest industry and its ability to compete.

TABLE 1

Examples of the impact of plantations on catchment streamflow compared with streamflow from unafforested catchments in South Africa (Scholes *et al.* 1995).

Ejemplos del impacto de plantaciones en los escurrimientos superficiales comparados con cuencas no forestadas en Sudafrica.

Natural catchment	Mean annual rainfall (mm)	Virgin mean annual runoff (mm)	Species and extent of afforestation (%)	Reduction in streamflow Age (yrs)	mm
Grassland	1634	880	*P. patula* - 75	0-29	360
Fynbos	1400	600	*P. radiata* - 57	0-23	200
Grassland	1150	250	*E. grandis* - 100	5	403
				9	Dry

Plantations of introduced species including eucalyptus and acacias have become a vital resource for offsetting, at least partly, India's wood crisis. As in several other countries, such developments meet informed and uninformed opposition and anxieties arising from conflicting demands on the land. The alleged impact of eucalyptus plantations on water availability in Karnataka State in India, has caused numerous arguments and conflicts, yet many farmers continue to plant eucalyptus for their economic benefit. These concerns have stimulated comprehensive research programs to examine the impact of plantations on the hydrological process in a tropical semi-arid region; comprehensive accounts of this work have been reported (e.g. Calder *et al.* 1992, Calder 1994, Calder 1996).

Research in South Africa, India, Brazil and South Australia shows that with knowledge it should be possible to locate and successfully manage plantations, taking into account the area planted in relation to catchment size, species, growth rates, stand management and overall economic and environmental benefits (Dye 1996, Calder 1994, Lima *et al.* 1996, Versfeld 1996). The development of plantation forests which threaten the availability of water for critical purposes will not be sustainable.

Assessment of sustainability. Despite the many and diverse views on sustainability, there is a broad and shared understanding of the fundamental elements (regarding) of sustainable forest management. How they should be assessed, what the agreed outcome should be, and what benefits there are and who should get them are subjects for ongoing debates. The idea of Criteria and Indicators (C&I) has emerged as a basis for providing a common understanding and an implicit definition of what constitutes sustainable forest management (Granholm *et al.* 1996). It is not an end in itself, but a tool for making progress towards sustainable management and it is intended to foster a common understanding of sustainability. *Sustainable management is a balancing act.*

There have been several initiatives, both at international and regional levels, to develop C&I as for example initiatives by specific organisations (e.g. Forest Stewardship Council), by consortia of national governments (e.g. Helsinki Process, Montreal Process), by an international research organisation (CIFOR, see Prabhu *et al.* 1996), and by national governments (e.g. France). Criteria are generally described as 'identified elements of sustainability - against which forest management can be assessed' (Prabhu *et al.* 1996). Criteria may deal with the extent and productivity of forests, their attributes and function, environmental benefits and socio-economic goods and services dependent on forests. One definition of an indicator is 'any variable or component of the forest ecosystem or the relevant management system used to infer attributes of the sustainability of the resource and utilisation' (Landres 1992, Prabhu *et al.* 1996). Examples of the indicators proposed by Prabhu *et al.* (1996) range from 'absence of ponding behind stream / river crossing' to 'there are assured compensation benefits in cases of accident'. These examples show the extraordinary wide range of indicators being considered. There can be several indicators for any selected criterion.

To assess progress towards sustainability, we need meaningful 'bench-marks' against which progress can be evaluated. The difficulties in establishing such 'bench-marks', using potential soil based indicators as examples, have been discussed previously (Nambiar 1996a, 1996c). Conclusions that we may draw on the net effects of plantations on environment and soil sustainability depend on the state of the ecosystem at the start. For example, for *P. radiata* plantations in Australia where the rates of production in second- and third-rotation crops are greater than those obtained for the first-rotation (Fig. 2 and 3), should the 'bench-mark' soil used for comparison be in the retained dry-sclerophyll native vegetation, part of which has been cleared for various purposes over decades? Should the comparison be with adjacent agricultural land which has been cultivated over the same period or should it be between IR - 2R - 3R pine plantation sites? Clearly, outcomes from measurements of changes in soil properties depend on the starting point. Furthermore, changes in some soil properties *per se* may have little relevance for the continued productive use of that land. Research narrowly directed to the discovery of sustainability indicators *per se* would not be a creative path for strengthening the knowledge required to improve sustainable practices. Research efforts for increasing wood production with environmental care would become more rewarding if we continuously strengthened our understanding of degradation, rejuvenation and enhancement processes in the ecosystem in relation to plantation management practices. That knowledge should be continuously relayed in a practical and operational context to managers through code of practices for management (Fig 6), which should be abided by all plantation enterprises

Along with global awareness of sustainability and international pressure for action, the move for C&Is was also pushed by the demand for 'eco-labelling' and other 'certification and labelling' ideas as a condition for market acceptance of exported / imported wood by the European-based environmentalist organisations? The momentum towards C&I and labelling has as much to do with politics as it has to do with sustainability

The foregoing discussion and the relationship between the degree of alignment and the level of risk described in Figure 6, emphasise the dynamic nature of the concept and practice of sustainability. The alignment will never be perfect, nor can we take it for granted that any low risk scenario will persist, once achieved. Plantation management systems should strive to ensure maximum alignment of the core goals (minimum risks to sustainability) as opposed to dysfunctions between values (high risks to sustainability). The way ahead for plantation forestry is unlikely to be as straightforward as the earlier foresters may have anticipated. There are genuine issues of equity, social justice and sustainability associated with plantations in some regions of the world and it is necessary for national governments to address them locally in a socio-political context. Profitability of industry and social justice may not go hand-in-hand. However, economic viability, environmental benefits and social goals are closely linked, and it is so with plantation forestry. Plantations in many cases compare favourably with other land uses, including crops and animal production, in terms of costs and benefits.

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