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BIOLOGICAL SUSTAINABILITY OF PRODUCTIVITY IN SUCCESSIVE ROTATIONS

Based on the work of

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CONTENTS

1. INTRODUCTION

This study examines the evidence for the biological sustainability of forest plantations. Biological sustainability is largely a silvicultural and forest management issue. Can forest plantations be grown indefinitely for rotation after rotation on the same site without serious risk? More specifically, can their long-term productivity be assured, or will it eventually decline over time? Are current intensive management practices, often with greater yields, more damaging than earlier practices? And does the better growth from these practices, along with rising atmospheric carbon dioxide, disguise evidence of site degradation or increasing risks from pests and diseases?

Understanding sustainability also applies to non-industrial uses of plantations. Does for example, the perpetual removal of leaves, twigs and litter from beneath tree stands, so widespread in India and China for example, degrade the site? What is the impact of management practices on other valuable non-timber products?

Specifically this paper addresses:

- What site changes may plantation forestry induce that threaten future rotations?
- What particular risks are tree plantations exposed to?
- What factual evidence is there for and against productivity change over time?
- What silvicultural interventions can help sustain yields?

The focus is on developing countries – a fuller analysis is given by Evans (1999b).

2 SITE CHANGE INDUCED BY PLANTATION FORESTRY

Two important questions are:

- Do common practices such as exotic species, monocultures, clear felling systems etc., cause site changes? and
- Are such changes more or less favourable to the next crop?

Dyck *et al.* (1994) and Nambiar and Brown (1997) have recently summarised recent research. Another older but useful references is Chijioke (1980). However, it is important to be cautious: tree rotations are long, even in the tropics, compared with most research projects! Furthermore, most research has been on conifer plantations.

2.1 Assessing changes in soil

It is usually difficult to establish conclusively what soil changes result from forestry practices. Sound baseline data are uncommon and it is frequently difficult to prove a link to plantation silviculture. There are remarkably few examples of changes supposedly induced by *growing* trees that lead to less favourable conditions for that species. Equally, the irreversibility of changes has rarely been demonstrated, apart from obvious physical losses such as erosion of topsoil. A gradual trend, perhaps observed over several decades, can be quickly reversed as stand conditions change. As Nambiar (1996) points out "the most striking impacts on soils and hence productivity of successive crops occur in response to harvesting operations, site preparation, and early silviculture from planting to canopy closure."

Most reports of site change in plantation forestry derive from matched plots. Increasingly today long-term experiments are being specifically designed to investigate change, e.g. CIFOR's tropics-wide study (Tiarks *et al*. 1998), the network in USA (Powers *et al*. 1994), and those monitoring gross environmental change such as the Europe-wide extensive and intensive forest monitoring plots (level 1 and level 11). Modelling is widely used but has limited precision because of the assumptions made.

The older observational approach is often biased as the investigation follows signs of poor tree growth or health. It also suffers from soils being notoriously variable in space and time. Single plot or small sample comparisons can be wildly unreliable. Improving reliability requires intensive sampling within a plot at specific times and matching many, not just a few, pairs of plots.

Thus there is great danger of drawing conclusions from limited investigations. Short-term studies in plantations can be grossly misleading, especially when extrapolated over whole or successive rotations.

2.2 Soil chemical status

Plantations may have three impacts:

- Nutrient removal from soil as trees grow and then are harvested;
- Changes in the chemistry of the soil surface from litter and organic matter being dominated by one species;
- Site preparation practices such as ploughing, drainage and fertilising which directly affect soil physical parameters and in turn nutrient and moisture availability.

2.2.1 Soil as a mineral store

Soils vary enormously as a nutrient reservoir, particularly when comparing fertile arable soils and associated crops to many forest situations. In forestry with perennial, often deep-rooted trees soil reserves are often less important than nutrient supply dynamics at the soil surface. Indeed, forests are highly efficient re-cyclers of nutrients and almost 'leak free' if undisturbed. In the tropics, where recycling is usually efficient, the biomass and organic matter, not the mineral soil, is the major store of nutrients. The soil - in both temperate and tropical areas - often is relatively unimportant for nutrient supply in mature plantations. It is the surface organic zone and topsoil with its fine roots, which is important in concentrating energy flow from decomposing organic matter back into plants. The integrity of this layer and how it is affected by human activities, including silviculture, is critical to sustainability.

2.2.2 Nutrient removal

Nutrient removal in plantations occurs when any product is gathered or harvested such as leaves, fruits, litter, logs or whole trees. Many studies have been made; Goncalves *et al.* (1997) alone list 12 tropical examples. The ratio of nutrient export to the nutrient store is a key measure of long-term ecosystem stability, although it is not straightforward to measure the store. For example, Lundgren (1978) found that *Pinus patula* plantations in Tanzania had annual removals of 40 kg ha^{-1} of nitrogen (N), 4 kg ha^{-1} of phosphorus (K), 23 kg ha^{-1} of potassium, 25 kg ha^{-1} of calcium and 6 kg ha^{-1} of magnesium. These rates of removal are about one-third of those of maize (Sanchez 1976) and in the Tanzania study represented less than 10 per cent of soil store i.e. a stability ratio of <0.1. In contrast, Folster and Khanna (1997) report data for *Eucalyptus urophylla x grandis* hybrid stands with three very different site histories in terms of the previous plantation crop(s) at Jari in NE Amazonia. To quote "Twelve of the stands were in the second to fourth rotation, indicating that most of the previously grown *Gmelina, Pinus* or *Eucalyptus* had already extracted their share of base cations from the soil and left it greatly impoverished." The stability ratio of >1 suggests non-sustainability. However, caution is needed. Others (e.g. Rennie 1955; Binns 1962; Johnson and Todd, 1990) have predicted from comparison of removals in harvested biomass with available quantities in soil that calcium nutrition will be a problem; yet trees continue to grow on soil where conventional soil analysis suggests there is virtually no calcium!

The impact of nutrient losses depends in part on what parts of the tree are actually removed - debarked log, log, whole tree including branches etc. - owing to the highly unequal concentration of nutrients in plant tissue. In general terms if the stability ratio is greater than 0.3 they may be serious stability questions in the longer term, and if it is above 0.5 in the immediate future.

Understanding these dynamics helps identify when, in the continuum of plantation productivities, sites, species and practices, the ratio becomes critical for long-term stability. There appear to be few examples of reaching such limits. It is worth remembering that nutrient removals by forest crops are typically only one-fifth to one-tenth that of arable farming (Miller 1995).

2.2.3 Litter and Residues

The influence of litter on soil chemical status may be important since leaves of different species decay at different rates. For example, in southern Africa substantial accumulations may develop under *P. patula* on certain sites (see Morris, 1993b) while this is unusual beneath the more lightly canopied *P. elliottii.* In broadleaved stands litter accumulation is uncommon though not unknown e.g. under some beech and oak stands on acid soils in Europe. Even under teak and *Gmelina,* which usually suppress all other vegetation, the large leaves readily decay. Similarly under the light crowns of eucalypts and ash (*Fraxinus* spp) and the nitrogen rich foliage of nitrogen-fixing trees such as *Acacia, Leucaena* and *Prosopis* spp, alders and casuarinas litter build up is rare.

Of greater importance than such long-term processes is how the litter and organic matter layers are handled, especially during site preparation and harvesting operations (see section 2.4).

2.2.4 Measured changes in soil chemistry

Most studies have either compared conditions before and after plantations were established or examined trends as a plantation develops. Few have examined changes over successive rotations and there are even fewer direct comparisons between plantations and farmland. Few consistent trends emerge.

In both temperate and tropical studies *increases* and *decreases* in carbon, nitrogen and macro-nutrients under plantations compared with natural forest or pre-existing conditions have been reported (Evans 1999b). Not surprisingly nitrogen accumulation is widely found under nitrogen fixing species.

Many studies in temperate plantations have focused on pH change, litter type, podzolization and so on. Recent investigations have concerned acid rain impacts, though distinguishing these from direct tree effects on soil acidity is difficult. On the whole, tree impacts are relatively small compared with the soil nutrient store (Evans 1999b).

2.3 Soil physical condition

Plantation forestry may impact soil physical conditions, and hence sustainability through
- site preparation and establishment operations;
- the effects of tree growth itself, and
- harvesting practices.

2.3.1 Site preparation and planting

Cultivation and drainage affect soil physics for many years and sometimes for more than one rotation. Obviously site preparation seeks to improve growing conditions for trees and not impair sustainability or productivity. Longer-term benefits include reduction in bulk density, increased infiltration capacity and aeration, improvement in moisture storage and enhanced mineralization rates of accumulated organic matter (Ross and Malcolm, 1982). Physical disruption of indurated layers and deep cultivation such as tining or ripping are actually designed to reverse 'undesirable' soil profile development. However, poor practices can be detrimental by topsoil removal or increasing erosion rates.

2.3.2 Impact of tree growth

The general conclusion about water use by trees, compared with grassland and many crops, is that trees have higher evapo-transpiration rates and thus 'use' more water. This has actually been harnessed to lower water tables. Eucalypts and other trees are planted for this purpose to control salinity.

However, it is difficult to quantify this effect on the growth of later rotations. If a plantation loses more moisture than is received in precipitation, soil moisture will not recharge and reserves are depleted. In the US mid-West many plantations established in the early 1900s initially thrived but died once moisture reserves were used up and precipitation was inadequate to sustain growth (Kramer and Kozlowski 1979).

Roots of trees are known to strengthen soils and reduce soil mass movement on hillsides.

2.3.3 Indirect impact of vegetation suppression

Plantations of teak and *Gmelina* in the tropics and many conifers, in both tropical and temperate conditions, may suppress all ground vegetation. Where this exposes soil, perhaps because litter is burnt or gathered, erosion rates increase. Under teak Bell (1973) found soil erosion 2½ to 9 times higher than under natural forest. The protective function of tree cover derives more from the layer of organic matter that accumulates on the soil surface than from interception by the canopy. In India, raindrop erosion was nine times higher under *Shorea robusta* plantations where litter had been lost through burning (Ghosh, 1978). Soil erosion beneath *Paraserianthes falcataria* plantations was recorded as 0.8 t $ha^{-1}y^{-1}$ where litter and undergrowth were kept intact but an astonishing 79.8 t $ha^{-1}y^{-1}$ where it had been removed (Ambar 1986). Wiersum (1983) found virtually no soil erosion under *Acacia auriculiformis* plantations with litter and undergrowth intact, but serious where local people gathered the litter. In Jamaica, Richardson (1982) reported that the dense needle mat under pine plantations was better than natural forest for minimising soil erosion.

2.3.4 Harvesting damage

Extracting trees from a site can cause soil compaction, scouring of soil surface and erosion, blocking of ditches and other drainage channels, and oil spillage. The method of extraction greatly influences the extent of damage with draft systems using mules, oxen etc being least harmful and skidding with tracked vehicles generally most damaging. Weather conditions and the type of soil also affect the severity of damage. Compaction often results from harvesting clay soils in wet conditions. There are many reports of impaired growth of planted trees on extraction routes and where soil has been compacted and suffered erosion (see Nambiar 1996).

2.4 Organic matter dynamics

The litter and organic matter layer at the soil surface is critical to sustainability for three reasons:

- the surface litter layer helps prevent soil erosion;
- litter and organic matter represent a significant nutrient store, albeit a dynamic one;

- the litter:organic matter:mineral soil interface with the topsoil is the seat of nutrient cycling and microbial activity.

Activities that disturb these organic matter roles can have large effects. Perhaps most serious of all is regular and frequent litter raking or gathering. In commercial plantation forestry managing debris during site preparation or after harvesting is costly, but as Nambiar (1996) states 'one shoddy operation can leave behind lasting problems'. The examples of yield decline discussed in section 3 usually include harmful practices to litter and organic matter.

2.5 Weed spectrum and intensity

Establishment and reestablishment of plantations greatly affects ground vegetation with many operations designed directly or indirectly to reduce weed competition. The objective of weed control is to ensure that the planted tree has sufficient access to site resources for adequate growth. Once canopy closure has occurred weed suppression is usually achieved for the rest of the rotation.

In subsequent rotations the weed spectrum often changes. Owing to past weed suppression, exposure of mineral soil in harvesting, and the accumulation of organic matter, conditions for weed species change. Birds and animals may introduce or spread new weed species, grass seed may be blown into plantations and accumulate over several years only to flourish when the canopy is removed. Roads and rides in plantations can become sources of weed seeds. Weed management must be an holistic operation. Often where yield declines have been reported in subsequent rotations the significance of changing weed competition has not been recognised.

3. OTHER PLANTATION RISKS

3.1 Pest and disease incidence in monocultures

A serious threat to plantations can arise from a massive build-up of a pest or disease. It has been disputed whether monocultures *per se* are more susceptible to such devastation (see Working Papers FP/3 and 10). An accepted ecological principle states that the stability of a community and its constituent species is positively related to diversity. Thus some argue that substitution of natural forest by even-aged monocultures may remove many of the natural constraints on local tree pest and pathogens and thus increase risk of attack. Some evidence supports this, see for example Gibson and Jones (1977) though these authors point out that increased susceptibility mostly arises from *conditions in plantations* rather than because only one tree species is present.

The relative susceptibility of monocultures to pests and disease is complex ecologically. For example, applying the idea that diversity is beneficial by cultivating mixed crops may not offer much protection since only small amounts of the right kind of diversity are needed to maintain stability (Way 1966). Further, the influence of diversity on stability of (say) insect populations depends on what population level is deemed acceptable. Often stable, equilibrium levels are too damaging and artificially low populations are sought. Pest controls to maintain low levels are very different from those required to achieve stability (Speight and Wainhouse 1989). These authors stress that artificially created diversity, i.e. mixed crops, does not necessarily improve ecological stability. It is certainly inferior to naturally occurring diversity; complexity of organisation and structure is as important (Bruenig 1986).

It is prudent, nevertheless, to spell out why plantations are perceived to be in danger.

1. Plantations of one or two species offer an enormous food source and ideal habitat to any pest and pathogen species adapted to them.

2. Uniformity of species and closeness of trees allow rapid colonization and spread of infection.

3. Very narrow genetic base e.g. one provenance or use of clones reduces the inherent variability in resistance to attack (see Working Paper FP/3).

4. Trees grow on one site for many years. This may allow a pest or disease to build up over time with little opportunity to destroy infection. The forest plantation cannot be changed quickly in face of a devastating outbreak.

5. Many plantations are of introduced exotic species and are without the insect pests and pathogens that occur in their native habitat. This has undoubtedly contributed to the great success of eucalypts across the tropics freed from numerous leaf-eating insects that occur in the Australian environment (Pryor 1976). Conversely, many natural agencies controlling pests and diseases are also missing and destruction can be swift and uncontrolled. Zobel *et al*. (1987) concluded that exotic stands are not more at risk, other than clonal plantations, and that problems arise mainly when species are ill suited to a site. Further, introducing biological control has been successful in many instances

There are several major examples where plantations have faced major disease or insect problems that have stopped the use of particular species or clones. For more detail (see Working Paper FP/10). While they may have prevented the planting of some species, impaired the productivity of others, overall they have not caused such widespread damage as to seriously question plantation silviculture as a practice.

There remain two concerns.

- Environmental change - changing climate and increasing atmospheric will add stress to established plantations while higher atmospheric nitrogen inputs may increase insect pest risk or diseases problems (Lonsdale and Gibbs 1996).
- New pests and diseases will emerge from a variety of sources (see Working Paper FP/10)

3.2 Risks associated with plantation forestry practices

Many pest and disease problems in plantations arise from the nature of forest operations, and not directly from growing monocultures.

First, extensive planting of one species, whether indigenous or exotic, inevitably results in some areas where trees are ill suited to the site and suffer stress. This sometimes occurs in large-scale planting programmes where insufficient attention is paid to sites or where exotics are used extensively before sufficient experience has been gained over a whole rotation e.g. *Acacia mangium* in Malaysia and Indonesia and the discovery of widespread heart rot.

Large amounts of wood residue from felling debris and the presence of stumps are favourable for colonization by insect pests and as sources of infection. There are many examples but modification of silviculture or application of specific protection measures generally contains such problems (Evans 1999b; Working Paper FP/10).

Thinning operations can damage remaining trees and provide infection sites for diseases. In the case of *Fomes* the stumps are colonised and this can lead to death of adjacent trees. Delayed thinning, ragged pruning, and poor hygiene can also increase risk to remaining trees. However, none seriously threaten plantation sustainability but emphasise the need for good husbandry (Evans 1992).

3.3 Storms and fire

Plantation uniformity possibly increases risk from hurricane and storm damage if only because trees may be planted in locations that increases their susceptibility. Sub-optimal productivity can result if a site's potential not fully realised. Minimising hurricane damage in the tropics can be helped by planting wind-firm species such as *Cordia alliodora* or choosing *Pinus caribaea* var *bahamensis* over *P. oocarpa*.

Most forest fires in plantations are caused by arson; only a few by lightning or encroachment of fires from neighbouring land. While there are a few examples of frequent fires preventing plantation development, it is more often due to poor community relationships than any inherent shortcoming with forest plantations.

4. EVIDENCE OF PRODUCTIVITY CHANGES

4.1 Productivity change in successive rotations of forest plantations

4.1.1 Data limitations

The long cycles in forestry make data collection difficult. Records are rarely maintained from one rotation to the next; funding for long term monitoring is often a low research priority; measurement conventions may change which confound ready comparison; detection of small changes is difficult; and often the exact location of sample plots is poorly recorded (Evans 1984). Moreover, few forest plantations are second rotation, and even fewer third or later rotation, thus the opportunity to collect data has been limited. Unfortunately without data it is difficult to demonstrate whether plantation silviculture is robust and genuinely determine the impacts of successive rotations.

The few comparisons of productivity between rotations have mostly been initiated because of concern over yields, namely 'second rotation decline', or about stand health. Thus the focus has been on problems, while the vast extent of plantations where no problems are recorded suggest that managers are not encountering obvious decline problems. Thus data available in the older literature may be biased to problem areas. More recent studies may be less so, such as the European Forestry Institute survey (Spiecker *et al.* 1996) and CIFOR's 'Site management and productivity in tropical forest plantations', as these incorporate systematic establishment of sample plots.

For forest stands hard evidence of productivity change over successive rotations is meagre with few reliable data. Information is available from only four major studies. There are also some anecdotal evidence or one-off investigations.

4.1.2 Spruce in Saxony and other European evidence

The first serious evidence of possible yield decline appeared in Germany in the 1920s but subsequent investigations have not confirmed an extensive problem. Indeed, in Europe today current growth rates generally exceed those of 50 years ago – see 4.2 below.

4.1.3 *Pinus radiata* in Australia and New Zealand

Significant yield decline in second rotation *P. radiata* appeared in South Australia in the early 1960s (Keeves 1966) with an average 30 per cent drop. In the Nelson area in New Zealand, on a few impoverished ridge sites there was transitory second rotation yield decline (Whyte 1973). These reports, particularly from South Australia, were alarming and generated a great deal of research. By 1990 it was clear for South Australia that harvesting and site preparation practices, particularly burning, which failed to conserve organic matter and an influx of weeds, especially grasses, in the second rotation were the main culprits. By rectifying these problems and using genetically superior stock second and third rotation pine now grow substantially better than the first crop (Boardman 1988; Nambiar 1996; Woods 1990). Elsewhere in Australia second rotation crops are mostly equal or superior to first rotation (Evans 1999b)

In New Zealand the limited occurrence of yield decline was mostly overcome by site preparation and establishment methods, such as using nursery stock rather than natural regeneration (A.D.G. Whyte and D.J. Mead pers. comm.). The decline could have been partly due to changing weed species. On the great majority of sites successive rotations have grown faster. Dyck and Skinner (1988) conclude that inherently low quality sites that are managed intensively may be susceptible to productivity decline.

4.1.4 *Pinus patula* in Swaziland

Long-term productivity research by the writer in the Usutu forest, Swaziland began in 1968 as a direct consequence of second rotation decline reports from South Australia. For 32 years measurements have been made over three successive rotations of *P. patula* plantations, grown for pulpwood, from a forest-wide network of long-term productivity plots (Evans 1996, 1999a, Evans and Boswell 1998). Plots have not received favoured treatment, but simply record tree growth during each rotation resulting from normal forest management over 62000 hectares by SAPPI Usutu.

The most recent analyses show second and third rotation growth data obtained from plots on exactly the same sites (Tables 1 and 2). First rotation growth data were derived from stem analysis and from paired plots and are less accurate: some of those data were reported in Evans (1996).

Table 1: Comparison of second and third rotation* Pinus patula *on granite and gneiss derived soils at 13/14 years of age (means of 38 plots).

Rotation	stocking (stems ha^{-1})	Mean height (m)	Mean DBH (cm)	Mean tree vol. (m^3)	Stand volume (m^{3}ha^{-1})
Second	1386	17.5	20.1	0.205	294
Third	1248	18.7	21.2	0.233	326
% change		+6.9	+5.5		+11.0

Source: updated from Evans (1999a)

Table 2: Comparison of second and third rotation* Pinus patula *on gabbro dominated soils at 13/14 years of age (means of 11 plots)

Rotation	Stocking (stems ha^{-1})	Mean height. (m)	Mean DBH (cm)	Mean tree vol. (m^3)	Stand volume (m^{3}ha^{-1})
Second	1213	16.7	20.0	0.206	244
Third	1097	16.8	21.7	0.227	255
% change		+0.5	+8.5		+4.5

Source: updated from Evans (1999a)

These results are from arguably the most accurate data set on biological sustainability. Over most of the forest where granite derived soils occur (Table 1) third rotation height growth is significantly superior to second and volume per hectare almost so. There had been little difference between first and second rotation (Evans 1978). On a small part of the forest (about 13% of area), on phosphate-poor soils derived from slow-weathering gabbro, a decline had occurred between first and second rotation, but this has not continued into the third rotation where there is no significant differences between rotations (Table 2).

No fertiliser addition or other ameliorative treatment has been applied to any of the long-term productivity plots. According to Morris (1987) some third rotation trees are probably genetically superior to the second rotation. However, the 1980s and especially the period 1989-92 have been particularly dry with Swaziland suffering a severe drought (Hulme 1996; Morris, 1993a). This will have adversely impacted third rotation growth.

The results are also important because silviculture was intensive as anywhere but with no thinning or fertilizers, the stands are monocultures, and the rotation of 15-17 years is close to the age of maximum mean annual increment. Large coupes are clearfelled and all timber suitable for pulpwood extracted. Slash is left scattered (i.e. organic matter conserved) and replanting done through it. So far, there is no evidence of declining yield. The limited genetic improvement of some of the third rotation could have disguised a small decline, but evidence is weak. Overall, the evidence suggests no serious threat to sustainability.

4.1.5 Chinese fir in sub-tropical China

There are about 6 million hectares of Chinese fir (*Cunninghamia lanceolata*) plantations in subtropical China. Most are monocultures and are worked on short rotations to produce small poles, though foliage, bark and even sometimes roots are harvested for local use. Reports of significant yield decline have a long history. Accounts by Li and Chen (1992) and Ding and Chen (1995) report a drop in productivity between first and second rotation of about 10 percent and between second and third rotation up to a further 40 percent. Ying and Ying (1997) quote higher figures for yield decline between first and second rotation of 29 per cent poorer height and 26 per cent less volume. Chinese forest scientists attach much importance to the problem and pursue research into monocultures, allelopathy, soil changes etc. Personal observation suggests that the widespread practices of whole tree harvesting, total removal of all organic matter from a site, and intensive soil cultivation that favours bamboo and grass invasion all contribute substantially to the problem. Ding and Chen (op. cit.) concluded that the problem is "not Chinese fir itself, but nutrient losses and soil erosion after burning (of felling debris and slash) were primary factors responsible for the soil deterioration and yield decline ... compensation of basic elements and application of P fertilizer should be important for maintaining soil fertility, and the most important thing was to avoid slash burning... These (practices) ... would even raise forest productivity of Chinese fir." (words in parentheses added by writer).

4.1.6 Teak in India and Java

In the 1930s evidence emerged that second rotation teak (*Tectona grandis*) crops were not growing well in India and Java (Griffith and Gupta 1948). Although soil erosion is widespread under teak and loss of organic matter through burning leaves is commonplace, the research into the ‘pure teak problem’, as it was called in India, did not generally confirm a second rotation problem. However, Chacko (1995) describes site deterioration under teak as still occurring with yields from plantations not coming up to expectation and a generally observed decline of site quality with age. He indicates four main causes: poor supervision of plantation establishment; over-intensive commercial taungya (intercropping) cultivation; delayed planting; and poor after-care. Chundamannii (1998) similarly reports decline in site quality over time and blames poor management. In Java site deterioration is still a problem and "is caused by repeated planting of teak on the same sites" (Perum Perhutani 1992).

Concern about successive teak crops, soil erosion and loss of organic carbon, has also been reported from Senegal (Mahuet and Dommergues 1960).

4.1.7 Southern pines in the United States

Plantations of slash (*P. elliottii*) and loblolly (*P. taeda*) pines began in mid 1930s as natural stands were logged out (Schultz 1997). With rotations of 30 years or more, some second rotations commenced in the 1970s. In general growth of the second crop was variable (Evans 1999b). A co-ordinated series of experiments, throughout the USA, is currently assessing long-term impacts of management practices on site productivity, but it is too early for results (Powers *et al.* 1994).

4.1.8 Other evidence

Other evidence is limited or confounded. For example, Aracruz Florestal in Brazil has a long history of continually improving productivity of eucalypts owing to an imaginative tree breeding programme so that regularly new clones are introduced and less productive ones discontinued (Campinhos and Ikemori 1988). The same is true of the eucalypt plantations at Pointe Noire, Congo (P. Vigneron pers comm.). Thus recorded yields may reflect genetic improvement and disguise any site degrade problem. It is clear that greatly increased productivities are being achieved in practice; the Aracruz sites appear capable of supporting productivities up to 60 or 70 $m^3ha^{-1}y^{-1}$.

In India (Das and Rao 1999) claims massive yield decline in second rotation clonal eucalypt plantations which the authors attribute to very poor silviculture.

At Jari in the Amazon basin of Brazil silvicultural practices have evolved with successive rotations since the first plantings between 1968 and 1982. A review of growth data from the early 1970s to present day suggest that productivity is increasing over successive rotations due to silvicultural inputs and genetic improvement (McNabb and Wadouski, in press).

In Venezuela, despite severe and damaging forest clearance practices, second rotation *Pinus caribaea* shows substantially better early growth than the first rotation (Longart and Gonzalez 1993).

4.2 Within-rotation yield class/site quality drift

For long rotation (>20 years) crops it is usual to estimate yield potential from an interim assessment of growth rate early in life and then to allocate a stand to a site quality class or yield class. A change from predicted to final yield can readily occur where a crop has suffered check or other damage in the establishment phase or fertiliser application corrects a specific deficiency. However, there is some evidence for very long rotation (>40 years) crops in temperate countries that initial prediction of yield or quality class will underestimate final production. Either the yield models used are now inappropriate or growing conditions are 'improving' in the sense of favouring tree growth. Across Europe the latter appears to be the case (Spiecker *et al*. 1996; Cannell *et al.* 1998) and is attributed to rises in atmospheric CO_2 and nitrogen input in rainfall, better planting stock and cessation of harmful practices such as litter raking.

Closely related is the observation that planting year is often positively related to productivity, with recent crops being more productive than older ones, regardless of inherent site fertility. This shift is measurable and can be dramatic, as seen, for example, in Australia (Nambiar 1998). Attempts to model productivity in Britain on the basis of site factors have often been forced to include planting date as a variable. Maximum mean annual increment of Sitka spruce increased with planting date in successive decades by 1 $m^3ha^{-1}y^{-1}$ (Worrell and Malcolm 1990) and for Douglas fir, Japanese larch (*Larix kaempferi*) and Scots pine (*Pinus sylvestris*) by 1.3, 1.6 and 0.5 $m^3ha^{-1}y^{-1}$ respectively in each succeeding decade (Tyler *et al.*, 1996). This phenomenon suggests that some process is favouring present growing conditions over those in the past - perhaps the impact of genetic and silvicultural improvements or cessation of harmful ones, and possibly the atmospheric changes mentioned above. Broadmeadow (2000) confidently predicts an increase in productivity for forests in United Kingdom owing to climate change.

The impact of these observations is that present forecasts of plantation yields are likely to be underestimates, as yields appear to be increasing. The one main exception, as noted earlier, is teak where initial site productivity estimates have been revised downward as stands age.

5 INTERVENTIONS TO SUSTAIN YIELD

The steady transition from exploitation and management of natural forest to increasing dependence on plantation forestry is following the path of agriculture. Many of the same biological means to enhance yield are available. They are outlined here with some covered in greater detail in Working Paper FP/3.

5.1 Genetic improvement

The forester only has one opportunity per rotation to genetically change his crop. These changes include:

- *Species change:* There are surprisingly few examples of wholesale species change from one rotation to the next, but it is sometimes used to increase yield or overcoming disease or insect problems.
- *Better seed origins, provenances, and land races:* This is widely used and usually results in increased vigour and perhaps greater pest and disease resistance. Countless studies affirm the benefits of careful investment in this phase of tree improvement.
- *Clonal plantations:* Some of the most productive tree plantations use clonal material, including both eucalypts and poplars. The potential productivity and uniformity of product gains make this an attractive approach. Roberds and Bishir (1997) suggest that using 30-40 unrelated clones would generally provide security against catastrophic failure.
- *Tree breeding:* Widely used to improve traits such as vigour, stem and wood quality, pest and disease resistance and frost tolerance. Tree breeding offers by far the greatest assurance of sustained and improved yields from plantations in the medium and long-term. Improvements in the order of 20 to 50 per cent are relatively easy to achieve (Franklin 1989). From plus-tree selection alone Cornelius (1994) reported genetic gain values of 15% in height and 35 % in volume. For example, in Zimbabwe a 30-year programme in sub-tropical pines led to first generation selections showing 15-20 percent yield increases and second generation selections having 30-35 per cent improvements.
- *Genetically modified trees:* No widely planted examples exist but the technique might be used to increase disease resistance, modified wood properties, cold or drought tolerance as opposed to increasing vigour directly.
- *Responding to environmental change:* Genetic improvement or changes offer a means of responding to climate change

5.2 Role of different silvicultures

Silvicultural knowledge continues to increase and while large yield improvements appear unlikely, incremental gains can be expected. Important examples are:

1. Stocking level manipulation to achieve greater output by fuller site occupancy, less mortality, and greater control of individual tree growth.

2. Matching rotation length to optimise yield may offer worthwhile gains.

3. In some localities prolonging the life of stands subject to windthrow by silvicultural means will increase yield over time.

4. Use of mixed crops may help in tree stability, may possibly lower pest and disease threats, but are unlikely to offer a yield gain over growing the most productive tree the site can support (FAO 1992).

5. Silvicultural systems that maintain forest cover at all times - continuous cover forestry practices - such as shelterwood and selection systems are likely to be neutral to slightly negative in production terms, while yielding gains in tree quality, aesthetics, and probably biodiversity value.

6. Crop rotation, as practised in farming, appears unlikely as a feature in plantation forestry. There are examples of plantations benefiting from a previous crop of nitrogen fixing trees such as *Acacia mearnsii.*

5.3 Fertilising

Regular application of mineral fertiliser is not presently a feature of plantation forestry. Most forest use of fertiliser is to correct known deficiencies e.g. micronutrients such as boron in much of tropics, and macronutrients such as phosphorus on impoverished sites in both the tropics and temperate zones.

Fertiliser application is likely to be the principal means of compensating for nutrient losses on those sites where plantation forestry practice does cause net nutrient export to detriment of plant growth.

5.4 Site preparation establishment practices

Ground preparation to establish the first plantation crop will normally introduce sufficient site modification for good tree growth in the long term. Cultivation *inter alia* loosens soil, improves rooting, encourages drainage, limits initial weed growth, improves water percolation, may reduce frost risk and, perhaps importantly for the long-term health of the forest, brings relatively unweathered soil minerals nearer to the surface and into the main feeding zone of tree roots. Thus substantial site manipulation is unlikely for second and subsequent rotations, unless there was failure first time round, except for alleviation of soil compaction after harvesting, and measures to reduce infections and pest problems.

Weed control strategies may change from one rotation to the next owing to differing weed spectrum and whether weeds are more or less competitive to planted trees. The issue is crucial to sustainability since all the main examples of yield decline reflect worsening weed environments, especially competition from grasses and bamboos. Deliberate over-sowing of cover crops to improve fertility, reduce erosion and control weeds is employed in agricultural plantation trees such as rubber. Similar strategies are sometimes used in *P. radiata* plantations.

Changes between rotations in treatment of felling debris and organic matter may occur such as cessation of burning, windrowing, or removal from site in whole-tree harvesting. What is clear is that the felling, harvesting and re-establishment phase is crucial to sustainable practice and needs to be viewed as a whole. The aim should be to minimise negative impacts due to compaction, loss of organic matter, soil erosion and nutrients.

5.5 Organic matter conservation

It is clear from many investigations that treatment of organic matter and care for topsoil both over the rotation and during felling and replanting is as critical to sustainability as is coping with the weed environment. While avoidance of whole tree harvesting is probably desirable on nutrition grounds, it is now evident that both prevention of systematic litter raking or gathering during the rotation and conserving organic matter at harvesting, are essential.

5.6 Holistic management

If all the above silvicultural features are brought together a rising trend in productivity can be expected. But if any one is neglected it is likely that the whole will suffer disproportionately. For example, operations should not exclusively minimise harvesting costs, but examine collectively harvesting, re-establishment and initial weeding as an holistic activity, so that future yield is not sacrificed for short term savings. Evidence of a rising trend reflecting the interplay of these gains is reported in Nambiar (1996) and Evans (1999b).

Holistic management also embraces active monitoring of pest and disease levels, and researching pest and disease biology and impacts will aid appropriate responses. Careful re-use of extraction routes to minimise compaction and erosion is a further example.

6 CONCLUSIONS

Four main conclusions can be drawn from this review which focuses mainly, but not exclusively, on narrow-sense or biological sustainability, conifers, and developing countries.

1. Plantations and plantation forestry practices do affect sites and under certain conditions may cause deterioration, but they are not inherently unsustainable. Care with harvesting, conservation of organic matter and management of the weed environment are critical features to minimise nutrient loss and damage to the soil.

2. Plantations are at risk from pest and diseases. The history of plantation forestry suggests that most risks are containable with vigilance and underpinning of sound biological research.

3. Measurements of yield in successive rotations of trees suggest that, so far, there is no significant or widespread evidence that plantation forestry is unsustainable in the narrow-sense. Where yield decline has been reported poor silvicultural practices and operations appear to be largely responsible.

4. Several interventions in plantation silviculture point to increasing productivity in the future, providing management is holistic and good standards maintained. Genetic improvement in particular offers the prospect of substantial and long-term gains over several rotations.

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