SUSTAINABILITY OF PRODUCTIVITY IN SUCCESSIVE ROTATIONS

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INTRODUCTION

Forest plantations are an increasingly important resource worldwide, a trend that is expected to continue strongly. This study examines the evidence concerning the 'narrow-sense' sustainability of forest plantations. It seeks to answer the question: is growing trees in plantations a technology that can work in the long term or are there inherent flaws biologically which will eventually lead to insuperable problems for such silviculture?

Sustainability

The question of sustainability in plantation forestry has two components. There are the general or broad issues of whether using land and devoting resources to tree plantations is a sustainable activity from the economic, the environmental or from the social sense. Is such development unsustainable or is it a threat rather than a help to people's livelihoods and way of life? These, and related issues, are important and fundamentally depend on national policies governing plantation development, understanding their impacts, and ensuring full public participation in the process. They contribute to what is labelled 'broad sense' sustainability.

The second component, 'narrow-sense' sustainability, is largely a silvicultural and forest management issue. The question raised is: can tree plantations be grown indefinitely for rotation after rotation on the same site without serious risk of reduction in site quality or in crop yield? More specifically, can their long-term productivity be assured, or will it eventually decline over time? These questions are pertinent owing to the increasing reliance on plantation forestry, but are also scientifically challenging since in previous centuries trees and woodlands were seen as 'soil improvers' and not 'impoverishers'. Are today's silvicultural and management practices more damaging because of shorter rotations and the high timber yields achieved, typically 2-4 times that of natural forest increment? And, of course, are developments such as tree breeding, targeted fertiliser application, and sophisticated manipulation of stand density, along with rising atmospheric carbon dioxide, likely to lead to crop yield improvement, while they disguise evidence of genuine site degradation or increasing risk of damaging attacks from pests and diseases?

Understanding sustainability also applies to non-industrial uses of plantations. Sustaining the numerous benefits people derive from planted trees should be a top priority and arise out of good management. Does the perpetual gathering and removal of leaves, twigs and litter from beneath tree stands, so widespread in India and China for example, simply loot the site of nutrients? And what of the flow of non-timber products, often of more value than wood, and perhaps less directly damaging to sites when harvested? These are relevant to plantation forestry, even if it is not always yet possible to answer such questions adequately.

This paper looks at evidence worldwide, but with a focus on developing countries, to address four elements of narrow-sense sustainability: a fuller analysis will be found in Evans (1999b). (a) What changes to a site may plantation forestry induces and hence threatens future rotations? (b) What particular risks are tree plantations exposed to? (c) What factual evidence is there for and against productivity change over time? (d) What silvicultural interventions can help sustain yields?

SITE CHANGE INDUCED BY PLANTATION FORESTRY - the biological, physical and chemical changes plantations may bring about

Two important questions are (1) do the silvicultural practices commonly applied, such as exotic species, monocultures, clear felling systems etc., cause site change, and (2) are such changes more or less favourable to the next crop? Does growing one crop influence the potential of its successor? [the assumption here is that the same spcies always follows the first rotation; discuion of the effect of changing species, either on the site or on the second species? Worth mentioning that most of the work done has been mainly with conifers?

This is a much researched topic and only the main themes are summarised. Two recent books have presented the science: Dyck et al. (1994) 'Impacts of forest harvesting on long-term site productivity', and Nambiar and Brown (1997) 'Management of soil, nutrients and water in tropical plantation forests'. It is important to be cautious: tree rotations are long, even in the tropics, compared with most research projects!

Assessing changes in soil

, It is usually difficult to establish conclusively both in fact and in scale that soil changes may have been caused by imposed forestry practices. An absence of sound baseline data is common and, moreover, even where figures are available, is the reported change actually induced by plantation silviculture?

The second question is whether the observed changes represent degrade or improvement. There are remarkably few examples of changes supposedly induced by *growing* trees (either the effect of actually planting the trees, or changes occurring during the rotation) 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 observational 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 suffers in precision at site level because of assumptions made.

The observational approach suffers bias in that investigation is often carried out specifically because there is a problem which has already revealed itself in poor tree growth or health. It also suffers from soils being notoriously variable, a difficulty exacerbated on many forest sites by the kind of ground often used for plantation forestry. Single plot or small sample comparisons can be wildly unreliable. Improving reliability in conditions of such variability must rely on intensive sampling within a plot and the matching of many not just a few pairs of plots.

A second, little recognised, source of variability is that measured values of many soil parameters can change radically during one year. Approximate matching of assessments dates appears as important as matching sites if valid conclusions are to be drawn.

The above points underline the danger of drawing conclusions from limited investigations covering only a few years of a rotation. Short-term studies can be grossly misleading especially when extrapolating over whole rotations and successive rotations in plantation forestry.

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 as the litter layer and organic matter are dominated by one species and hence uniform composition and decay characteristics; and site preparation practices such as ploughing, drainage and fertilising which directly affect soil physical parameters and in turn nutrient and moisture availability.

Soil as a mineral store

Soils vary enormously in their role as a nutrient reservoir. Thinking has been much conditioned by arable farming that treats soils as a medium in which to grow crops where nutrient supply is largely maintained by annual fertiliser inputs; and by the fact that in most temperate soils the store of plant nutrients far exceeds that in the above-ground biomass. In forestry, where fertiliser inputs are limited and trees perennial and generally deep rooting, the focus is less exclusively on soil reserves and more on where the dynamics of nutrient supply is mediated - i.e. largely at the soil surface. Indeed, forests are highly efficient re-cyclers of nutrients and almost 'leak free' if undisturbed. In the tropics, where recycling can be at its most efficient, nutrients in mineral soil often no longer represent the dominant proportion of the ecosystem. The soil - in many temperate as well as tropical regions - often plays only a small part in the nutrient exchange and it is the surface organic, root-bearing zone, especially the annual turnover of fine roots, which is important in concentrating energy flow from decomposing organic matter back into living organic matter. The integrity of this layer and how it is handled in plantation silviculture is critical to sustainability.

Nutrient removal

Nutrient removal in plantation forestry occurs when any product is gathered or harvested such as leaves, fruits, litter, bgs or whole trees. Many studies have been made; Goncalves *et al*. (1997) alone list 12 tropical examples. Critical to plantation sustainability is what proportion the nutrients lost represent of the whole store. This ratio of nutrient export : nutrient store is advocated as key measure of long-term ecosystem stability, (though it rather begs what is the store and how it can be measured?). For example Lundgren (1978) found that *Pinus patula* plantations in Tanzania led to 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 is >1 and suggests it is unstable and unsustainable. 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 on many factors, but crucial is 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 at what points on the continuum of plantation growth throughout the world of sites, species and productivities 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, see Miller (1995).

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 accumulation of litter 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 leguminous trees such as *Acacia*, *Leucaena* and *Prosopis* spp. and non-legume N-fixers such as alders and casuarinas litter build up is rare owing to rapid decay of the rich organic matter.

Of greater importance than the above long-term impacts is how the litter and organic matter layers are handled, especially during harvesting operations and this is reviewed below.

Measured changes in soil chemistry

The above processes indicate that plantation forestry practice could influence soil chemical status, but what has been observed? Most studies have either compared conditions between plantation sites and those before 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 farm land. 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 - see references in Evans (1999). Not surprisingly nitrogen accumulation is widely found under nitrogen fixing species.

Huge numbers of studies in temperate plantations have focused on pH change, litter type, podzolisation 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.

Soil physical condition

Plantation forestry may impact soil physical conditions, and hence sustainabilty through (1) site preparation and establishment operations, (2) the effects of tree growth itself, and (3) harvesting practices.

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 mineralisation rates of accumulated organic matter (Ross and Malcolm, 1982). Physical disruption of indurated layers and deep cultivation such as tining are actually designed to reverse 'undesirable' soil profile development.

Impact of tree growth

The general conclusion about water use by trees is that compared with grassland and many farm crops trees exhibit higher evapo-transpiration i.e. the 'use' more water. On some sites this has actually been harnessed to dry it and lower the water table: there are instances of eucalypts planted for this purpose.

However, it is difficult to quantify this effect on the growth of later rotations. If a plantation loses more moisture than is received by the site in precipitation, no soil moisture recharge will occur 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).

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, rain drop erosion was 9 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.

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 with compaction often following extraction operations conducted in wet conditions on heavy high clay content soils.

There are many reports of impaired growth of planted trees on extraction routes and where soil has been compacted and suffered erosion: a useful summary will be found in Nambiar (1996).

Organic matter dynamics

What happens to the litter and organic matter layer at the soil surface is critical to the question of sustainability for three reasons:

1. the surface litter layer helps prevent soil erosion;
2. litter and organic matter represent a significant nutrient store, albeit a dynamic one;
3. the litter:organic matter:mineral soil interface is the seat of nutrient cycling and microbial activity.

Any activity that disturbs these roles in the ecosystem can have large effects of which perhaps most serious of all, and still practised in some countries, is regular and frequent litter raking or gathering. In commercial plantation forestry the cost of managing debris and site preparation when restocking plantations is expensive and a high proportion of the establishment costs, but as Nambiar (1996) points out 'one shoddy operation can leave behind lasting problems'.

The examples of yield decline noted later usually include harmful practices regarding litter and organic matter.

Weed spectrum and intensity

Establishment of plantations greatly affects ground vegetation with many operations are 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. A critical next phase is managing the weed problem through the harvesting and restocking process in re-establishing the crop.

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. As with a failure to handle organic matter carefully, where yield declines have been reported, often the significance of weeds has been insufficiently recognised on restocked sites in second or third rotations.

RISKS PLANTATIONS ARE EXPOSED TO

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 much disputed whether monoculture itself is more susceptible to devastation from these causes. The broadly accepted ecological principle of stability dates back to the 1950s and is that the stability of a community and its constituent species is positively related to it diversity. Following this reasoning foresters have stressed that substitution of natural forest by even-aged monoculture plantations 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 organic damage 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). Also 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 sought. Pest control to maintain low levels are very different from those required to achieve stability (Speight and Wainhouse 1989) as every spray to every farmers' field testifies. These authors stress that artificially created diversity, i.e. mixed crops, does not necessarily improve ecological stability and 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. Food supply is a basic ecological determinant of population size and multiplicity of sites for breeding or infection favour rapid population build-up.

2. Uniformity of species and closeness of trees including branch contact above ground and root lesions in the soil, allow rapid colonization and spread of infection. Canker diseases that are splash dispersed or mist-carried and insects with small effective spread are favoured by proximity of hosts.

3. Narrow genetic base in plantations e.g. one provenance or no genetic variation (e.g. clones) reduces the inherent variability in resistance to attack.

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. Many argue, however, that exotic plantations experience a period of relative freedom from organic damage, perhaps for the first one or two rotations. Zobel's et al (1987) analysis of the threat to exotics concluded that evidence does not confirm that stands are more at risk, other than clonal plantations, and that problems arise mainly when species are ill-suited to a site.

Examples of devastating outbreaks of fungal disease and insect pests

1. *Dothistroma* needle blight of *Pinus radiata* plantations in the East African highlands curtailed plantings from 1950s despite its superior growth rate to *P. patula* and *Cupressus lusitanica.*

2. Diplodia (*Sphaerosis sapinea*) kills pines in southern Africa if there is severe infection of tissue damaged by a violent hail storms.

3. In Europe poplar canker (bacterial infection from *Xanthomonas populi*) and leaf rusts (*Melampsora* spp.) restrict by law commercial use of poplars to a few relatively resistant species.

4. In the 1980s outbreaks of the severely defoliating insect (psyllid) *Heteropsylla cubana* devastated plantations of *Leucaena leucocephala*, especially where Hawaiian hybrids were used, and this once widely planted nitrogen-fixing tree is now far less important.

5. Attempts to grow mahogany (*Swietenia* spp.) and other Meliaceae family species (*Cedrela, Khaya, Melia, Toona,* etc), in plantation, has been often thwarted by stem deformation from the mahogany shoot borer *Hypsipyla* spp.

6. In the 1990s widespread defoliation and death of cypress trees (*Cupressus lusitanica*) was caused by the cypress aphid (*Cinara cupressi*) in the industrial plantations of Kenya and Tanzania (Ciesla, 1991).

7. In the 1970s the native pine beauty moth (*Bupalus piniaris*) killed whole plantations of young pole-stage *Pinus contorta* growing on deep peats in north Scotland.

These few examples [for others see for example Ciesla (1994)] illustrate the scale and potential threat pest and diseases represent. They have prevented the planting of some species, impaired the productivity of others, but overall have not caused such widespread damage as to seriously question plantation silviculture as a practice.

There remain two serious concerns. 1. Environmental change - changing climate, increasing atmospheric pollutants of CO_2 and nitrogen compounds, will add stress to established plantations while higher nitrogen inputs may increase insect pest risk and diseases problems (Lonsdale and Gibbs, 1996). 2. New pests and diseases will emerge: a) from new hybrids or mutations; b) from new introductions arising from increasing global trade e.g. *Cryphonectria* canker in eucalypts in S. Africa and new phytophthoras in Britain; and c) from native pests adapting to introduced trees.

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 one species of tree in a uniform way (monoculture).

Harvesting and other residues

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, several are cited in Evans (1999), but modification of silviculture or application of specific protection measures generally contain such problems.

Site and species selection

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 may occur where large monospecific blocks are planted 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.

Thinning and pruning damage

Thinning operations can damage remaining trees and provide infection courts for diseases and, in the case of Fomes infection as stumps are colonised and through root lesions, lead to death of adjacent trees. Delayed thinning, ragged pruning, and poor hygiene can also increase risk to remaining trees; several examples are cited in Evans (1992a) but none seriously threaten plantation sustainability, but emphasis the need for good husbandry.

Storms and fire

Plantation uniformity possibly increases risk from hurricane and storm damage if only because trees may be planted in locations which increase their susceptibility. Sub-optimal productivity can be the result and a site's yield 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 finally preventing plantation development, it is more to do with relations with the local community than any inherent shortcoming with forest plantations.

EVIDENCE OF PRODUCTIVITY CHANGE

Productivity change in successive rotations of forest plantations

Problems with data

For forest stands (crops) hard evidence of productivity change over successive rotations is meagre with few reliable data. 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 os 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: the vast extent of plantations where no records are available suggest no great concern and that managers are not encountering obvious decline problems. Thus data available in the older literature may be biased to problem areas while 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', that incorporates systematic establishment of sample plots.

Review of evidence comparing yields in successive rotations.

Four major studies have reported productivity in successive rotations along with some anecdotal evidence and occasional one-off investigations. These are grouped by region with emphasis here on developing country experience

Spruce in Saxony and Other European Evidence

In the 1920s Wiedemann (1923) reported that significant areas of second and third rotation spruce (*Picea abies*) in lower Saxony (Germany) were growing poorly and showed symptoms of ill-health. In 8 per cent of plantations there was a fall of two quality classes in second and third rotation stands. It is now clear that this mainly arose from planting spruce on sites to which it was ill-suited. Today, young stands of pure spruce in Saxony and Thuringia are growing more vigorously than equivalent stands 50 or 100 years ago (Wenk and Vogel, 1996).

Elsewhere in Europe comparisons between first and second rotations are limited. In Denmark Holmsgaard *et al*. (1961) indicated no great change for either Norway Spruce or beech though today second rotation beech is growing significantly better (Skovsgaards and Henriksen, 1996). In the Netherlands second rotation forest generally grows 30 per cent faster than the first (van Goor, 1985) and in Sweden second rotation Norway Spruce shows superior growth (Eriksson and Johanssen, 1993; Elfing and Nystrom, 1996). In France decline is reported in successive rotations on *Pinus pinaster* in the Landes though it is not attributed to site deterioration (Bonneau, *et al.* 1968). In Britain most second rotation crops are equal to or better than their predecessor and no decrease in growth is expected (Dutch, pers. comm.). Recent evidence points to UK conifer forests growing faster than they used to (Cannell, *et. al.* 1998).

Pinus radiata *in Australia and New Zealand*

Significant yield decline in second rotation *Pinus radiata* appeared in South Australia in the early 1960s (Keeves, 1966) with an average 30 per cent drop in most forests in the state. 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 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 - see summary in Evans (1999)

In New Zealand the limited occurrence of yield decline was mostly overcome by cultivation and use of planted stock rather than natural regeneration (Whyte pers comm). On the great majority of sites successive rotations gain in productivity. Dyck and Skinner (1988) conclude that inherently low quality sites that are managed intensively will continue to be susceptible to productivity decline.

Pines 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 *Pinus patula* plantations, grown for pulpwood, from a forest-wide network of long-term productivity plots. Plots have not received favoured treatment, but simply record tree growth during each rotation resulting from normal forest management by the SAPPI Usutu .

The most recent analysis appear in Evans (1996, 1999a) and in Evans and Boswell (1998). Tables 1 and 2 (simplified and updated from Evans, 1999a) show second and third rotation growth data obtained from plots on exactly the same sites. First rotation growth data were derived from stem analysis and from paired plots and are less accurate: some of these data are 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 (*S*/ha)	Mean ht. (m)	Mean DBH(cm)	Mean tree vol. (m^3)	Vol/ha (m^3ha^{-1})
Second	1386	17.5	20.1	0.205	294
Third	1248	18.7	21.2	0.233	326
% change		+7.1	+5.6		+11.0

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 (*S*/ha)	Mean ht. (m)	Mean DBH(cm)	Mean tree vol. (m^3)	Vol/ha (m^3ha^{-1})
Second	1213	16.7	20.0	0.206	244
Third	1097	16.8	21.7	0.227	255
% change		+0.05	+8.3		+4.6

source: modified from Evans (1999a)

These tables summarise results from arguably the most accurate datasets available on narrow-sense 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 difference between rotations (Table 2).

The importance of the Swaziland data, apart from the long run of measurements, is that no fertiliser addition or other ameliorative treatment has been applied to any long-term productivity plot from one rotation to the next. According to Morris (1987) some third rotation *P. patula* is probably genetically superior to the second rotation. However, the 1980s and especially the period 1989-92 have been particularly dry, Swaziland suffering a severe drought along with the rest of southern Africa (Hulme 1996, Morris, 1993a). This will have adversely impacted third rotation growth. These data are also of interest because plantation silviculture practised in the Usutu forest over some 62,000 ha is intensive with pine grown in monoculture, no thinning or fertilising, and on a rotation of 15-17 years which is close to the age of maximum mean annual increment. Large coupes are clear felled and all timber suitable for pulpwood extracted. Slash is left scattered (i.e. organic matter conserved) and replanting done through it at the start of the next wet season. These plantations are managed as intensively as anywhere and, so far, there is no evidence to point to declining yield. The limited genetic improvement of some of the third rotation could have disguised a small decline, but evidence is weak. Also, it can be strongly argued that without the severe and abnormal drought growth would have been even better than it is. Overall, the evidence suggests no serious threat to narrow-sense sustainability.

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 per cent and between second and third rotation up to a further 40 per cent. 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. However, mensurational data are difficult to obtain, but Chinese forest scientists attach much importance to the problem and pursue research into monoculture, allelopathy, and detailed study of 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.) conclude 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).

Teak in India and Java

In the 1930s evidence emerged that replanted teak (*Tectona grandis*) crops (second rotation) 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.

Elsewhere concern about successive teak crops, soil erosion and loss of organic carbon, has also been reported from Senegal (Mahuet and Dommergues, 1960) and in Java, Indonesia, where there are about 600,000 ha of teak, site deterioration is a problem and "is caused by repeated planting of teak on the same sites" (Perum Perhutani, 1992)

Southern pines in the United States

Plantations of slash (*P. elliottii*) and loblolly (*P. taeda*) pines are extensive in the southern states. Significant plantings began in mid 1930s as natural stands were logged out (Schultz, 1997) and with rotations usually 30 years or more, some restocking (second rotation) commenced in the 1970s. In general growth of the second crop is variable - see examples in Evans (1999). A coordinated 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).

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 and dedicated 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 patently 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 one recent report (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).

Within-rotation Yield Class/Site quality drift

Two recently observed phenomenon require comment.

Inaccuracy in predicted yield

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 outturn, i.e. the crops grows better in later life than expected. 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.

However, as noted earlier, the opposite is occurring with teak. High initial site quality estimates do not yield the expected outturn and figures are revised downward as the crops get older.

Relation of quality (yield) class with time of planting

Closely related to the above is the observation that date of planting 9i.e. proximity to the present0 is often positively related to productivity i.e. more recent crops are more productive than older ones regardless of inherent site fertility. This shift is measurable and can be dramatic, see example from Australia in 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, such as the impact of genetic and silvicultural improvements (and again cessation of harmful ones) and possibly the 'signature' of 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 two related observations is that present forecasts of plantation yields are likely to be underestimates; yields appear to be increasing. The one main exception is teak.

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 only briefly and are summarised for their potential to increase productivity, to alleviate threats, and to suggest what best practice is.

Genetic improvement

The forester only has one opportunity per rotation to change his chosen crop. Change in species, seed origin, use of new clones, use of genetically improved seed and, in the future, genetically modified trees all offer the prospect of better yields in later rotations.

Species change

There are surprisingly few examples of wholesale species change from one rotation to the next which suggests that in most cases foresters have been good silviculturists. Foru examples for pine species are cited.

1. Changing from native *P. sylvestris* to *P. nigra* var. *maritima* for the second rotation in Thetford forest, UK led to a yield increase from about 10 to 13 $m^3ha^{-1}y^{-1}$.

2. Replacing *P. pinaster* in the Landes region of France with *P. nigra* raised yield and improved stem quality and hence outturn of millable timber.

3. In Swaziland on sites where *P. patula* was replaced by *P. taeda* for the third rotation, little yield improvement occurred but it may be economically attractive as a cheaper tree to grow (Evans, 1999b).

4. In Queensland, Australia, use of pine hybrids of *P. elliottii* X *P. caribaea* var. *hondurensis*

are used operationally in place of the pure species on sites with impeded drainage. It has led to both increased vigour and better stem quality.

Better seed origins, provenances, and land races

The impact of all these genetic improvements will affect yield and outturn directly and indirectly through better survival and greater suitability to the site which may lead to 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 world's most productive tree plantations use clonal material, including both eucalypts and poplars. It is clear that both the potential productivity and the uniformity of product make this silviculture attractive. Although clonal forestry has a narrow genetic base, careful management of clone numbers and the way they are interplanted can minimise pest and disease problems. Roberds and Bishir (1997) suggest that use of 30-40 unrelated clones will generally provide security against catastrophic failure.

Tree breeding

Through an array of selection, crossing, and propagating techniques traits can be favoured that may improve vigour, stem and wood quality, pest and disease resistance and other parameters such as frost tolerance. There are many notable examples of successful tree improvement strategies most of which are only beginning to bear fruit owing to long tree rotations and the slow process of tree breeding, particularly in orchard establishment and promotion of flowering, and in field testing of selections and progenies. Nevertheless, genetic tree improvement offers by far the greatest assurance of sustained and improved yields from plantations in the medium and long-term. It is commonly believed that 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 based on 24 published reports. For example, in Zimbabwe a sustained 30 year programme of tree improvement of sub-tropical pines has led to first generation selections showing 15-20 per cent yield increases and second generation selections to 30-35 per cent improvements.

Genetically modified trees

There are no widely planted examples at present where genetic engineering has modified trees. The expectation is that these techniques will be used to develop disease resistance, modified wood properties, cold or drought tolerance as opposed to direct increase in vigour.

Responding to environmental change

Genetic improvement or changes offer a means of responding to climate change. For genetics to fulfil this role an active breeding programme is necessary and it must be based on a wide genetic diversity. Part of the programme should not only be selection and multiplication but also deliberate maintenance of a broad genetic base. This may require new collections of material from across the whole of a species' natural range.

Role of different silvicultures

Silvicultural knowledge continues to increase through research and field trials and greater understanding of tree and stand physiology. While large yield improvements appear unlikely, incremental gains can be expected. Important examples include the following:

1. Manipulation of stocking levels to achieve greater output of total fibre, or a particular product such as high quality sawlogs, by fuller site occupancy, less mortality, and greater control of individual tree growth.

2. Matching rotation length to optimise yield - the rotation of maximum mean annual increment - offers worthwhile yield gain in many cases.

3. In some localities, such as the British Isles, prolonging the life of a 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 although there are examples of tree plantations benefitting from a previous crop of nitrogen fixing legumes such as *Acacia mearnsii*. The expectation must be that industry will require a similar not widely differing species when replanting.

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 many parts of both the tropical and temperate the world. In most instances fertiliser is only required once in a rotation.

Monitoring of nutrient levels in foliar analysis or fertiliser trials have a role, but probably only as an aid to good overall silviculture not as a diagnostic growth promotion tool. 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.

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 (above) reflect worsening weed environments, especially competition from grasses and bamboos.

Changes between rotations in treatment of felling debris and organic matter may occur such as cessation of burning, use of windrowing, or removal from site in whole-tree harvesting. Where the consequences and impacts of such changes are informed by research e.g. modelling the greater nutrient removal in whole tree harvesting, then a conscious evaluation can be made. What is clear however is that the felling, harvesting and re-establishment phase is crucial to sustainable practice and needs to be viewed as a whole with the aim of seeking to minimise impacts from compaction along extraction routes, from loss of organic matter and from soil erosion and nutrient loss.

Organic matter conservation

It is clear from many investigations that treatment of organic matter both over the rotation and during felling and replanting is as critical to sustainability as 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.

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 i.e. 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) for Australia and reproduced in Evans (1999a) along with an example from Swaziland.

Holistic management also embraces active monitoring of pest and disease levels, and researching pest and disease biology and impacts will aid appropriate responses such as altering practices e.g. delayed replanting to allow weevil numbers to fall. Careful re-use of extraction routes to minimise compaction and erosion is a further example.

Conclusion

There are several interventions in plantation silviculture which 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.

CONCLUSIONS

Four main conclusions can be drawn from this review. [mention that it is mainly concerned with conifers? and the need to distinguish the effects of conifers, which are more likely to be negative, from broadleaves?]

1. Plantations and plantation forestry practices do affect sites and under certain conditions may cause deterioration, but 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 conditions.

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. [stress the importance of matching species or provenance to site, maintaining the stand in a vigorously growing condition through weeding and thinning etc]

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.