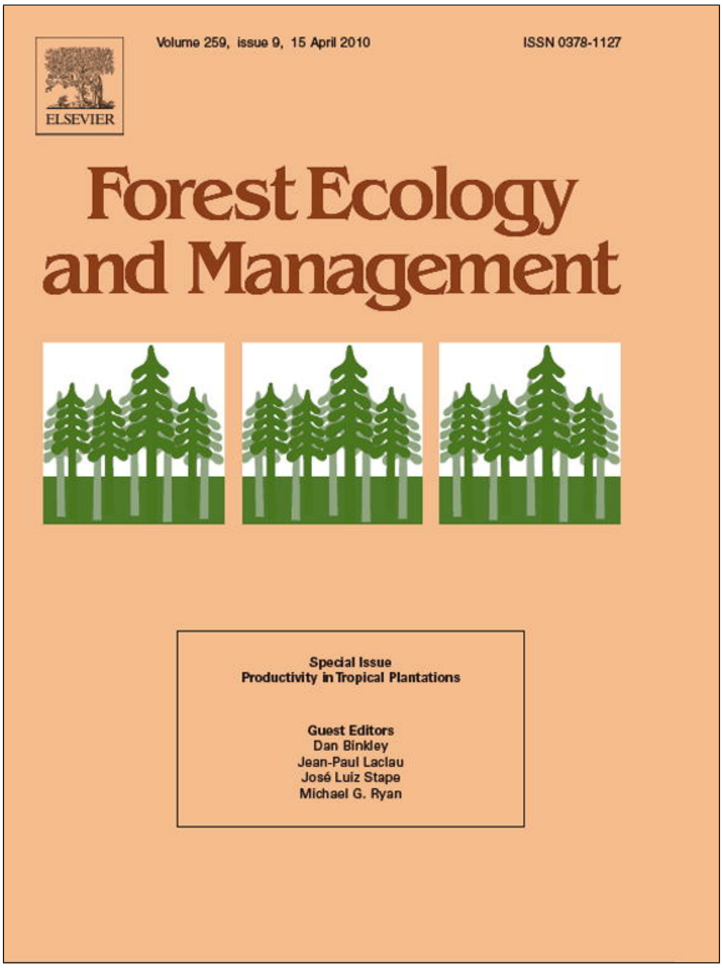

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Intensive, site-specific silviculture: Manipulating resource availability at establishment for improved stand productivity. A review of South African research

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ABSTRACT

An important window of opportunity to increase and sustain productivity in short-rotation plantations is the period from felling through re-establishment to canopy closure. This paper explores the effects, interactions and response mechanisms of intensive silvicultural practices on plantation productivity and sustainability, using five South African case studies (a–e). (a) Land preparation trials showed that complete surface cultivation by ploughing had a significant beneficial effect when afforestation is done for the first time in grasslands, improving basal area growth by 11–52% over pitting only. However, similar treatments have not resulted in significant growth responses under re-establishment conditions. (b) Stand growth suppression resulting chiefly from soil compaction during mechanised harvesting operations is strongly related to soil type, soil textural class and residue management options. Volume growth reduction in short-rotation eucalypt crops ranged from 25% on compaction sensitive loamy soils to less than 2% in resistant sandy soils. (c) The response mechanism whereby vegetation management improves stand productivity is a reduction in both inter-specific and intra-genotypic competition for resources, as well as a decrease in stand variability. Operationally, the most important criteria in a vegetation management programme relate to the timing of control operations across diverse site conditions. In local trials, the primary factors controlling the time taken for competition-induced tree growth suppression to occur were related to altitude, slash burning and the interaction between these factors, which facilitated the development of regional vegetation management strategies. (d) Empirical fertilizer trials in short-rotation hardwood stands have shown significant improvements in final productivity (commonly 20–90 $m^3\,ha^{-1}$ in eucalypts and 30–50 $m^3\,ha^{-1}$ in *Acacia*), as well as wood density (15–30 $kg\,m^{-3}$ for eucalypts) following improvements in early nutrition. Improved nutrition was achieved through fertilization at planting or indirectly through residue management. The response mechanism is primarily due to early canopy development and associated increases in light capture, coupled with a more modest increase in canopy quantum efficiency and above-ground carbon allocation on a dry site. On sites with abundant water supply, increased quantum efficiency is likely to be the dominant response mechanism. (e) A series of operational gains trials tested the interactive effect of genetic tree improvement, site–genotype interaction, stand density and vegetation management + fertilization on eucalypt stand growth across five sites. There were no significant interactions between factors, but importantly, the results were additive, emphasizing the need to optimise each practice in the value chain to achieve maximum productivity.

1. Introduction

South African forestry areas are widely distributed and predominantly scattered on the eastern seaboard of the country. This area has a complex physiography with wide variations in geology, soil types, rainfall, temperature and evapotranspiration, which results in large variations in resource availability to trees. The site diversity has necessitated the testing of a range of different hardwood species that can be grown commercially. The country also has a growing, rapidly urbanising population of more than 45 million people. However, new afforestation in South Africa has declined since 1990, with the total planted area showing a gradual

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decline from 1.49 M ha in 1996 to 1.27 M ha in 2007 (Godsmark, 2008). The bulk of the hardwood plantation area in the summer rainfall zone of South Africa (589 000 ha) is managed as unthinned, short rotations for predominantly pulpwood (470 000 ha) and also mining timber (68 000 ha) production (Godsmark, 2008). The bulk of this area consists of eucalypt stands and approximately 102 000 ha is planted to *Acacia*. Increasingly, commercial forestry competes for land with other land uses such as agriculture, conservation, urban development and infrastructure. Increasing the productivity of existing plantations is thus necessary to supply the growing consumption of wood and fibre in the country and it offers the largest potential for reducing the unit cost of wood production. Strategies for achieving this goal in short-rotation plantation systems include genetic tree improvement as well as improved harvesting and silvicultural practices, e.g. minimizing negative impacts of mechanised operations and implementing appropriate soil tillage, slash management, fertilization and vegetation management treatments. In addition, it is important to optimise the stand density and rotation length for each site type and to match the most suitable genotype to available sites to ensure optimum productivity from a shrinking land base (Schönau, 1984, 1989). An important window of opportunity to increase productivity and to ensure sustainability in unthinned, short-rotation plantations is the period from felling through re-establishment to canopy closure. In this paper, we explore the effects, interactions and possible response mechanisms of several intensive silvicultural practices and strategic silvicultural choices (in the broader sense) on forest productivity and sustainability, using a number of South African case studies on the *Eucalyptus* and *Acacia* plantations.

The pulpwood plantations of South Africa have many similarities to short-rotation plantations or so-called “fibre farms” in several countries of the southern hemisphere and southeast Asia, e.g. Brazil, Chile, Argentina, Uruguay, Congo, Australia, Indonesia, India, southern China and Vietnam (Nambiar and Kallio, 2008; Tables 1 and 2). In all these areas, comparatively dense, unthinned stands of *Eucalyptus* and/or *Acacia* genotypes are often planted under intensive silvicultural management which frequently includes site preparation, vegetation management with mechanical and/or chemical means as well as supplementary fertilization. However, the situation in South Africa is somewhat different in several aspects. The mean annual precipitation for the bulk of SA's pulpwood plantations ranges between 700 and 900 mm per annum, which can be considered as being on the drier end of the spectrum of vast plantations areas of the southern hemisphere and southeast Asia, e.g. south-central Chile, eastern Brazil, Indonesia, north-eastern Argentina, Tasmania and south-western India and southeastern China (Stape, 2002; Sankaran et al., 2008; Hardiyanto and Wicaksono, 2008; FAO, 2009). The relative abundance of shale, mudstone and dolerite derived soils, combined with slightly lower rainfall conditions in SA may also be partly responsible for levels of base cations in soils that are mostly adequate to support fast stand growth rates, albeit low levels by agricultural standards (Table 1). Indeed, a fairly low percentage of significant responses has been obtained in SA fertilizer trials with potassium, calcium or magnesium as treatments (du Toit and Carlson, 2000; du Toit, 2002), whereas the application of one or more of these elements are commonplace in many plantations of Brazil, for example (de Barros et al., 2004). Furthermore, the bulk of SA's pulpwood plantations are found at medium to high altitudes, in contrast to the lower altitudes in many other warm temperate and sub-tropical countries (Table 1). The stand densities used in SA are generally similar or slightly higher than those in some southern hemisphere countries, e.g. Australia and some areas of Brazil (Table 2). High stand densities can produce slightly higher volume growth per unit area in short rotations than international standards, but this volume will be comprised of smaller individual tree sizes. The harvesting of smaller tree sizes becomes economically more attractive where comparatively light harvesting machinery and a fair amount of manual labour is used, which is the case in SA. Higher stocking can also contribute towards minimizing the time taken to achieve canopy closure with savings on re-establishment weed control.

2. Results from South African case studies

2.1. The effect of land preparation on short-rotation hardwood stand growth

Intensive land preparation operations became an essential part of forest management in South Africa over three decades ago, in part due to the adoption of early research results that purported clear benefits of tillage for rapid early stand growth of hardwoods (e.g. Schönau et al., 1981). Much of this early work was critically reviewed in the late 1990s by Smith (1998) and subsequently re-analysed and published (Smith et al., 2000, 2001b). Care was taken to ensure that the effects of tillage would not be confounded with weed control effects: (a) in most trials, weed control was implemented across all plots, and (b) in trials with weed control as a factor, only those treatment combinations that included weed control were used during re-analysis (Figs. 6 and 7 in Smith et al., 2000). The work reported on the wide range of land preparation techniques that were previously tested in trials both under establishment (formerly agricultural land and grassland) and re-establishment conditions in *Eucalyptus* plantations. These included ploughing, ripping, subsoiling, ridging and complete site preparation (de-stumping, ripping and discing) treatments *inter alia*.

At establishment, where trees are planted for the first time, surface cultivation operations (such as ploughing) were the most effective method of establishment for a wide range of *Eucalyptus* species realising growth improvements of between 11 and 52% in final basal area over pitting only (Smith et al., 2000; Fig. 1). It was believed that improvements in growth were primarily due to nutrient mineralization and the physical break up of the dense root mat of the grassveld by surface ploughing. Smith et al. (2000) also showed that growth responses to ripping and subsoiling were markedly erratic since the effectiveness of these operations was dependent upon soil type, soil water conditions at time of tillage and implement design. In most trials no further improvement in growth was noted when ripping/subsoiling was carried out in addition to surface cultivation and there was little evidence to

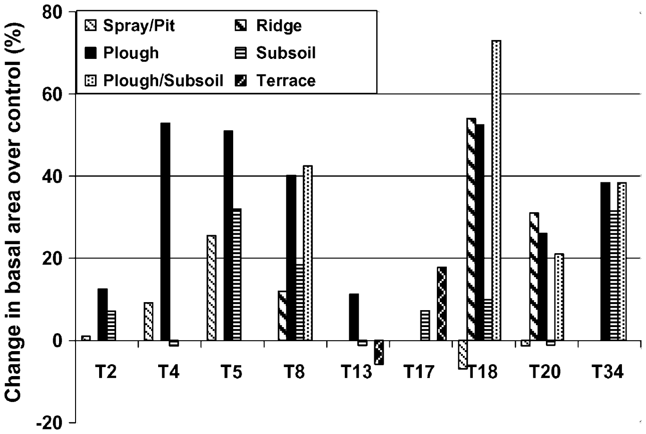

Fig. 1. The effect of land preparation treatments on the growth of *Eucalyptus* spp. established in native vegetation. Growth change is expressed as a percentage change in basal area relative to the pitting treatment (Smith et al., 2000). T2–T34 indicate the original trials from Smith et al. (2001a,b).

suggest that ripping through a stone layer had any beneficial effect on growth.

A review of land preparation trials carried out under re-establishment showed that intensive site preparation has not resulted in major growth improvements of *Eucalyptus* stands across a range of site types (Smith et al., 2001b; Fig. 2). In some cases the authors showed that inappropriate land preparation resulted in a reduction in stand productivity because of negative effects on the soil. It was suggested that the lack of major growth responses is due to most South African soils under forest plantations being characterised by a friable consistence, well micro-aggregated structure, high porosity coupled with low bulk densities (Smith et al., 2001b) and beneficial perforation effects of tree roots from previous rotations (Nambiar and Sands, 1990; Powers, 1999).

Research and experience have shown that perceived growth-limiting factors (such as stone layers and "hardpans") were not limiting productivity in the first place and the methods employed to correct them, e.g. subsoiling, terracing and ridging, simply increased the risk of failure particularly if subsequent silvicultural management was subsequently poor, for example poor weed control (Smith, 1998). In addition, the high costs of these operations can place forestry enterprises at risk of financial failure.

2.2. The effect of harvesting operations on short-rotation hardwood stand growth

Harvesting operations during clearfelling and extraction of timber from commercial plantations may result in changes in long-term site productivity due to soil compaction and residue manipulation (Powers, 1999). In the past two decades a number of trials have addressed these issues by implementing harvesting treatments (felling and extraction) during clearfelling of *Eucalyptus* stands. Treatments included forwarding, mechanical felling, in-field mechanical stacking, cable yarding and grapple skidding *inter alia*. In some instances growth on extraction routes was compared to that of adjacent areas. In general, the extent to which soil compaction has resulted in growth losses is closely related to the soil type. Volume growth of *Eucalyptus* can be reduced by as much as 25% at clearfelling (11 years of age) on sensitive soils that have an even textural distribution such as sandy loams/loams/sandy clay loams (Smith, 2000, 2003; Fig. 3). Growth declines following compaction on these soils are mainly due to compaction having a negative effect on the soil strength and available water capacity (AWC) of such soils (Hill and Sumner, 1967; Smith et al., 1997, 2001a). However, even high levels of compaction did not affect growth to the same extent on very sandy soils and clay soils. On very sandy soils (<5% clay content), penetrometer soil strength rarely becomes limiting for root growth. The effects of compaction on AWC are very dependent upon soil texture. With increasing compaction (comparing values midway between extraction roads with those in the extraction road) AWC was lower at Nseleni (sandy loam), similar at KT (loamy sand) and increased at Rattray (sand; Smith, 2003; Fig. 4).

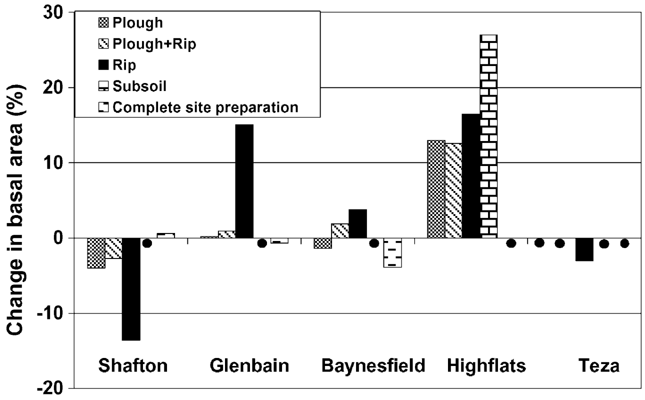

Fig. 2. The effect of land preparation treatments on the growth of *Eucalyptus* spp. re-established on plantation land. Growth change is expressed as a percentage change in basal area relative to the pitting treatment (Smith et al., 2001a,b). Dots indicate absence of treatment in a particular trial.

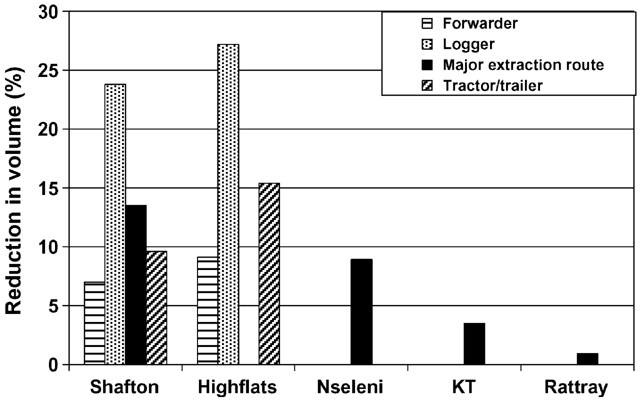

Fig. 3. The effect of harvesting operations on the growth of *Eucalyptus grandis* at clearfelling for five sites in South Africa. Growth change is expressed as a percentage change in volume compared to where no disturbance took place. Adapted from Smith (2003, 2006) and Smith and du Toit (2005).

A feature of the results on sensitive sites is that the volume growth curves for the various treatments are diverging with time typical of a Type II response described by Snowdon and Waring (1984), Snowdon (2002) (Fig. 5). This response type refers to a significant change in the volume growth potential of the stand which keeps diverging from the untreated control for the entire rotation length. This indicates that for certain soil types, soil compaction may lower site productivity in the long-term (Smith, 2006). Research data have also shown that harvesting operations may affect stand productivity by their effect on soil organic matter and the forest floor rather than soil compaction alone (Smith and du Toit, 2005).

More recent work has shown that early *Eucalyptus* growth was significantly affected by the interaction between the residue management and compaction treatments. The importance of retaining residues on sites after harvesting has been amply demonstrated since retaining residues can reduce the effects of soil compaction (Rietz et al., 2006), reduce the need for fertilization (du Toit and Dovey, 2005; Smith and du Toit, 2005) and retain nutrient capital on sites with low nutrient pools thus improving site productivity (Deleporte et al., 2008; Gonçalves et al., 2008; Mendham et al., 2008; Nambiar and Kallio, 2008). Therefore, the

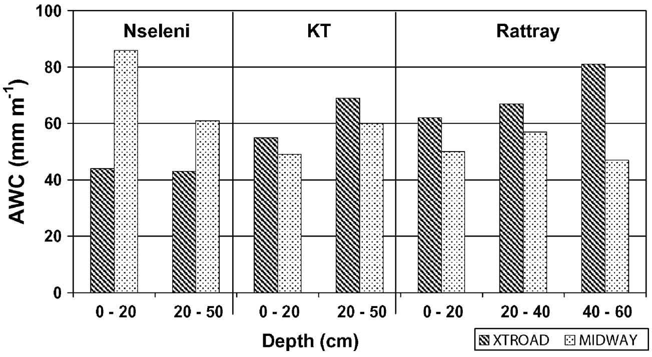

Fig. 4. The effect of soil compaction in extraction roads (XTROAD) and uncompacted areas (MIDWAY) on available water capacity (AWC) for two soil depths at three trial sites in South Africa (from Smith, 2003).

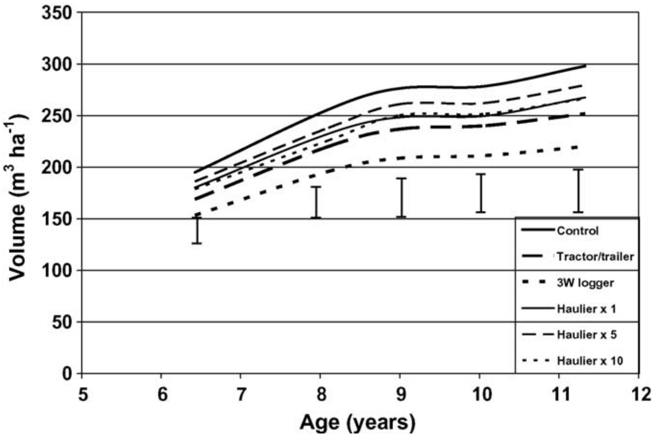

Fig. 5. Volume development of *E. grandis* versus time for six harvesting extraction treatments on a compaction-sensitive soil in South Africa (from Smith, 2006). Least significant differences at $p < 0.05$ are presented for the last five measurement dates.

effect of harvesting operations on long-term site productivity should be seen not only in terms of physical impact but in terms of the nature and distribution of residues retained on site.

2.3. Effects of harvest residue management and fertilization on stand productivity

Research on fertilizer use in South African plantations started as early as the 1920s (Williams, 1928; Osborn and Williams, 1929). More specifically, during the last half century, there has been substantial experimentation with fertilizers *at time of establishment*, which covered a wide range of species, site types and establishment conditions. Summaries of results from these empirical fertilizer trials on hardwood plantations have been documented by Schönau et al. (1981), Schönau (1983, 1989), Herbert and Schönau (1989, 1990), Noble and Herbert (1991), Herbert (1996), Carlson et al. (2001), du Toit et al. (2001), du Toit (2002), du Toit and Oscroft (2003), and du Toit and Drew (2003). Fertilization at establishment has the potential to substantially boost the productivity of short-rotation hardwood crops. Levels of application at this time is usually expressed on a per tree basis since fertilizer is placed in a localised application next to each transplant, irrespective of stocking, which can range from 1100 to 2400 stems ha^{-1} in short-rotation *Eucalyptus* and *Acacia* stands. Optimum applications usually fall in the range 0–30 g N tree^{-1} (rarely up to 50 g N tree^{-1}); 10–20 g P tree^{-1} and 0–15 g K tree^{-1}, depending on soil type, site conditions and harvest residue management (Table 2). Most of the documented responses show that an increase in timber volume on a mature (6–10 year old) eucalypt rotation can vary form 20 to 90 m^3 ha^{-1} with a concurrent increase in wood density of 15–30 kg m^{-3} (Schönau, 1983; Herbert and Schönau, 1989, 1990; Herbert, 1996; Carlson et al., 2001; du Toit et al., 2001; du Toit and Oscroft, 2003; du Toit and Drew, 2003). However, there are a number of examples of early hardwood experiments that did not respond significantly to fertilizer applications, where the experiments were abandoned without reporting the non-response in the formal literature. In some of these cases, the lack of response had been attributed to drought or low rainfall conditions. For mature (8–11 year old) *Acacia mearnsii* stands, corresponding responses commonly ranged between 30 and 50 m^3 ha^{-1} following a single application of P or PK at time of establishment, depending on soil type (du Toit, 2002). The observation that early improvements in resource availability to eucalypt stands can increase volume growth and wood density simultaneously has drawn attention to the high returns that can be obtained from an investment in fertilization since both effects are beneficial to pulp producers. The term fibre production has been defined as the product of stand volume growth, wood density and screened pulp yield to gauge the overall benefits of silvicultural treatments to pulp production (Clarke, 2001). An example of this overall effect of fertilization at establishment on the possible improvements in fibre production in a series of *E. grandis* × *urophylla* trials on the Zululand coastal plain is shown in Fig. 6.

The nutrient availability to a newly planted tree stand varies with several site factors and the optimum fertilizer mixture should complement inherent nutrient availability under the prevailing conditions. For example, the N supply potential of soils apparently increases with increasing organic matter content in the topsoil, making it unnecessary to supply large quantities of N in the form of fertilizer at establishment on humus-rich soils (Noble and Herbert, 1991). However, a process-based understanding of nutrient dynamics across stand age classes and widely varying site types in the country is currently still very limited. More detailed, site-specific research on macronutrient dynamics will be needed to further improve future fertilizer recommendations. Preliminary results show that surface cultivation increases nutrient mineralization thus decreasing the young transplant's dependence on artificial fertilization (Schönau et al., 1981). Disturbance and incorporation of harvest residue into the topsoil by the action of certain harvesting machinery may also increase the mineralization rate of residues which provides an early flush of readily available nutrients, thus also decreasing the need for early fertilization in such areas (du Toit and Dovey, 2005; Smith and du Toit, 2005). Of all residue management treatments, slash burning is responsible for the greatest increase in the availability and uptake of N, P, K, Ca and Mg in the short term (up to 1 year after treatment), which may rival the tree growth response obtainable with fertilization at establishment (du Toit and Dovey, 2005; du Toit et al., 2008). While this result may hold for colder climate sites where organic matter tends to accumulate, the long-term impact of nutrient losses through burning may outstrip it short-term benefits on sensitive sites with low organic matter contents. In addition to applying fertilizer sources that would supplement and balance the inherent nutrient supplying potential of the site, it is necessary to optimise the application rate, timing and method of application for

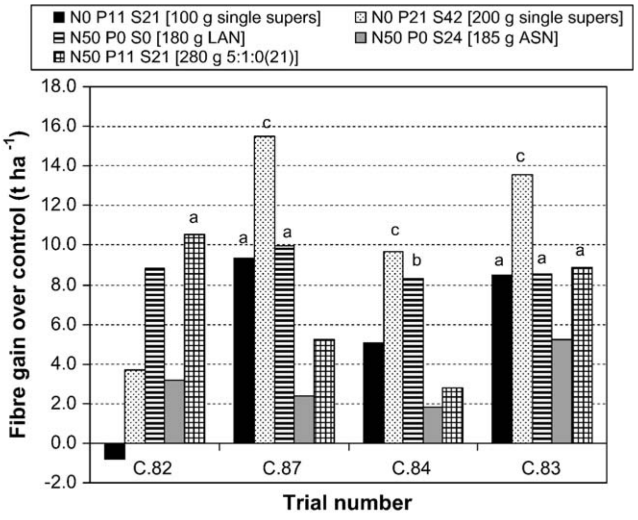

Fig. 6. Increases in fibre production (tons of screened pulp ha^{-1}) over the unfertilized control treatments across four *Eucalyptus grandis* × *urophylla* trials on the Zululand coastal plain after applying various combinations of nitrogen, phosphorus and sulphur. Elemental levels in the legend are in g tree^{-1}; fibre yield of the control treatments vary between 86 and 92 t ha^{-1} and original trial numbers are arranged on a gradient of soil organic matter from very low (C.82, left) to moderate (C.83, right), after du Toit and Oscroft, 2003. Letter codes a, b and c indicate significant responses over the control at $p < 0.05$; $p < 0.01$ and $p < 0.001$, respectively.

maximum return on investment (du Toit, 1995, 2002; du Toit and Carlson, 2000).

The mechanism of the response to improved nutrition in young stands (brought about by various residue management operations and fertilization) was investigated by du Toit (2008) on a site with comparatively low soil water availability by international plantation standards. This mechanism was contrasted to published studies on eucalypts with similar objectives conducted on sites with more abundant water supply (Giardina et al., 2003; Stape et al., 2008). All three studies measured leaf area index, intercepted radiation and canopy quantum efficiency at the scale of the stand over several years. On the dry (South African) site, improved nutrition allowed for a rapid increase in leaf area index (LAI) during the first 2.5 years only, thereafter LAI remained similar across treatments. Expressed in terms of the production ecology equation, the response hinged on large increases in absorbed radiation with modest changes in quantum efficiency and biomass partitioning. In strong contrast, young eucalypt stands on sites with abundant water supply (Hawaii and Brazil) responded to improved nutrition with very large improvements in quantum efficiency and modest improvements in light absorption or partitioning to woody biomass (Giardina et al., 2003; Stape et al., 2008; du Toit, 2008). On dry sites, it thus appears that the window of opportunity to improve production is to enhance nutrition in newly planted stands, i.e. when water requirements are still low and soil water supply is not yet a limiting factor (du Toit, 2008). The woody biomass development on the dry site was typical of a Type I response (Snowdon, 2002). This response type does not cause a sustained improvement in volume growth, but merely enhances the stage of stand development (i.e. peak MAI stays approximately the same as the untreated control but it is reached in a shorter time). Several empirical experiments in South Africa that manipulate the availability of growth resources at time of establishment (fertilizer, site preparation and vegetation management experiments with eucalypts) have shown a similar response type, i.e. a decrease in the time taken for the trees to "capture" the site through canopy closure (e.g. Herbert and Schönau, 1990; Noble, 1992; Schumann, 1992).

2.4. Stand growth response to vegetation management treatments

The presence of vegetation during the establishment of *Eucalyptus* plantations may result in sub-optimal tree growth through competition for light, water, nutrients and growing space (Zutter et al., 1987; Endo and Wright, 1992; Little et al., 2003a; Wagner et al., 2006). To determine the impact of competing vegetation on eucalypts when grown across a range of sites in the summer rainfall regions of South Africa, a number of trials were implemented during the 1990s. Both the short- and long-term results from these trials have highlighted the importance of vegetation management during establishment on subsequent tree growth (Little et al., 2002; Little and van Staden, 2003; Little, 2008), the effect of selective vegetation control on tree growth (Little, 2003, 2008), the minimum areas that need to be kept free from competing vegetation in order to achieve optimum growth (Little and Schumann, 1996), and interaction between site, associated vegetation and subsequent tree growth (Little et al., 2007; Little and Rolando, 2008). These and other trials have led to the implementation of intensive vegetation management regimes in South African plantations which is primarily based on herbicide applications, with limited use of mechanical, cultural and/or biological weed control measures.

In addition, Little et al. (2003b) were also able to demonstrate the negative impact that weed competition during establishment had on long-term stand dynamics when comparing tree growth in a weedy (non-weeded treatment) and weedfree treatment (no weed competition) in a fast growing eucalypt stand. Inter-specific and intra-genotypic competition were evident in the weedy treatment at different stages of tree development, but only intra-genotypic competition occurred in the weedfree treatment. Inter-specific competition resulted in greater variability between the trees in the weedy treatment (which developed a bimodal size class distribution) by the time canopy closure had occurred. The differentiation in tree size was further enhanced by asymmetric intra-genotypic competition once the trees had become established. Thus the long-term consequences of poor establishment weed control not only affected the final volume (weedfree, 223.9 $m^3\ ha^{-1}$; weedy, 137.8 $m^3\ ha^{-1}$), but also the tree form/taper (weedfree, 0.842 cm m^{-1}; weedy, 0.672 cm m^{-1}), site index (weedfree, 16; weedy, 14 [values indicate the topheight of trees at a reference age of 5 years]) and variability (weedfree, 21.8%; weedy, 36.9% [the co-efficient of variation was used to indicate variability]) (Little et al., 2003a,b).

Collectively, the above research has also provided insight into the degree of tree growth suppression that occurs in response to the diversity of site-related competitive vegetation. However, from a management perspective, one of the greatest difficulties associated with controlling competitive vegetation during establishment relates to the timing and planning of vegetation management operations, as well as the structuring of vegetation control budgets to suit the requirements of a wide range of sites. This is partly due to the diversity of sites utilised for commercial tree production in South Africa (Table 1), where there is variability in terms of species composition, abundance and growth, local climatic conditions, methods of site preparation and previous land use (van Heerden and Mason, 1991; Mason, 1993; Jarvel and Pallett, 2002; Small and McCarthy, 2002; Taverna et al., 2005). Little et al. (2007) showed that altitude, the method of site preparation (burning versus not burning slash prior to planting) and the interaction between these two factors were related to the timing of tree growth suppression during the establishment of eucalypt plantations. Regardless of the method of site preparation, the onset of competition-induced tree growth suppression occurred sooner at lower altitudes, where the vegetation was more diverse and vigorous in terms of growth (refer to Table 1 for the relationship between site conditions and altitude). At higher altitudes only, slash burning was found to stimulate the earlier growth of vegetation, reducing the time for competition-induced tree growth suppression to occur. That previous land use affects plant species distribution is well documented (Dupouey et al., 2002; Lundgren et al., 2004; Windeballe et al., 2004). In the summer rainfall region of South Africa, plant species common to land previously used for agriculture include sedges (*Cyperus* spp.), grasses (*Panicum maximum*) and herbaceous annuals (*Bidens pilosa*, *Conyza* spp.) that are very competitive during the first few months following planting (Little and Schumann, 1996; Little and van Staden, 2003).

The understanding gained regarding changes in competition-induced tree growth suppression across an altitudinal gradient, together with the results from the site-specific vegetation management trials, indicated the potential to structure vegetation management operations on a regional or zonal level (Table 1). The principal advantage of a regional management system being an associated reduction in costs, as control operations could be structured to meet an expected level of competition. Five eucalypt trials were thus initiated to test the applicability of these standards when utilised on a commercial scale. One of the trials was situated at a lower altitude site (65 m a.s.l.; sub-tropical zone), two at mid-altitude sites (878 and 1262 m a.s.l.; warm temperate zone), and two at higher altitude sites (1469 and 1590 m a.s.l.; cool temperate zone). Each trial was planted to a genotype that was suited to the specific site conditions. Several vegetation management treatments

Table 1
Major climate zones and broad overview of plantation forestry site types in the summer rainfall area of South Africa.

Climatic zone & sub-divisions	Altitudinal range with latitudinal strata[a] (m)	Mean annual temperature range[b] (°C)	Common range in mean annual precipitation (mm)		Most common geological types[d]	Most common soil types, their organic carbon (OC) levels, base status (BS), and other characteristics[e]
			Dry sites[c]	Wet sites[c]		
Cool temperate (CT 1–9)	2250–1400 (N)	10–16 (general snow & frost risk)	700–800	800–925	Highveld granites	Low OC, low BS, highly leached sandy clays and clays in catenary association (red soils on uplands, yellow soils with mottled plinthic subsoils in between and grey soils on poorly drained bottomlands)
	1950–1350 (C) 2200–900 (S)				Sandstone Shales/mudstone	Moderate OC, low BS, apedal, well drained clay soils
Warm temperate (WT 1–9)	1600–800 (N)	16–19 (frost confined to hollows)	850–900	950–1000	Shales	Moderate OC, low BS, apedal, well drained yellow clays
	1500–800 (C)				Dolerite/diabase	Moderate OC & BS, apedal, well drained red clayey soils
	1300–50 (S)				Sandstone	Low OC & BS, weakly developed sandy lithosols on rock
					Lowveld granites	Low OC & BS, deep apedal, well drained clay loams
Sub-tropical (ST 1–9)	1050–450 (N) 900–400 (C) 100–0 (S)	19–22 (frost free)	925–975	1025–1200	Aeolian sands	Very low OC, low to very low BS, deep, infertile sands and loamy sands

BS = sum of topsoil exchangeable base cations (cmol$_c$ kg^{-1}), where <3 is classed as very low; 3–5 as low; 5–15 as moderate and >15 as high (information for this table was compiled from Smith et al., 2005a; Ellis, 2000 & interrogation of the unpublished soils database of the Inst. for Comm. For. Res.).

[a] Broad ranges for the northern (N; 22–26°S), central (C; 26–28°S) and southern (S; 28–33°S) sections (only for areas where plantation forests occur).

[b] Duration of frost period 1–3 months in CT and <1 month in WT zones.

[c] Classified as "dry, moist or wet" according to precipitation, with a sliding scale linked to the mean annual temperature range.

[d] Geological parent material groupings are related to soil texture, soil base cation status and topsoil organic carbon content, which are major factors influencing soil water storage potential, soil fertility and soil resilience.

[e] OC = organic C of topsoil (0–20 cm; measured in g kg^{-1}), where <10 is classed as very low; 10–25 as low; 25–60 as moderate and >60 as high.

developed to suit the predicted vegetation load at each site were implemented and varied according to either weeding intensity (high, moderate and low), or the area around the tree that was kept free of vegetation (no vegetation control, a row weeding and complete vegetation control). The area cleared around each tree in the row weeding ranged from 3.75 to 4 m^2 and weedy biomass in the untreated controls (t ha^{-1}) ranged from 0.9 to 1.8 in the cool temperate, 3.0 to 3.1 in the warm temperate and reached 4.3 in the sub-tropical zone. Following tree crown closure at each trial, tree growth was linked to the level of vegetation management in each treatment and its associated total cost up to canopy closure, allowing for the development of different cost–benefit comparisons. Results from this series of trials (Little and Rolando, 2008) showed that the intensity of vegetation management required to produce significant growth benefits decreased with increasing altitude (associated with cooler temperature regimes) (Fig. 7 and Table 2), as did the area that needed to be kept free from competing vegetation. In contrast to the two higher altitude sites, where tree growth did not benefit from vegetation management, a significant increase in tree growth occurred for the high and moderate intensity vegetation management operations at the three mid- and lower altitude sites. Besides demonstrating the commercial applicability of research results, this series of trials has shown that site dependent vegetation management is viable on a commercial scale and will allow the South African forest industry to adjust their weed control budgets on a regional basis (linked to altitudinal zones).

2.5. The additive nature of genetic tree improvement and several silvicultural operations

An operational gain trial series was established across five sites within the temperate areas of KwaZulu Natal in South Africa to increase the level of understanding of the interaction of these cultural practices together with genetically improved material on a range of sites for species other than *E. grandis* (Boreham and Pallett, 2007). A 2^4 factorial design (randomised complete block) with two replications was established at each of the five trial sites, where the main factors tested at each site were species selection, genetic improvement, silvicultural intensity and planting density. The treatments are briefly discussed in the text that follows. The first choice or recommended species for each trial site as well as an

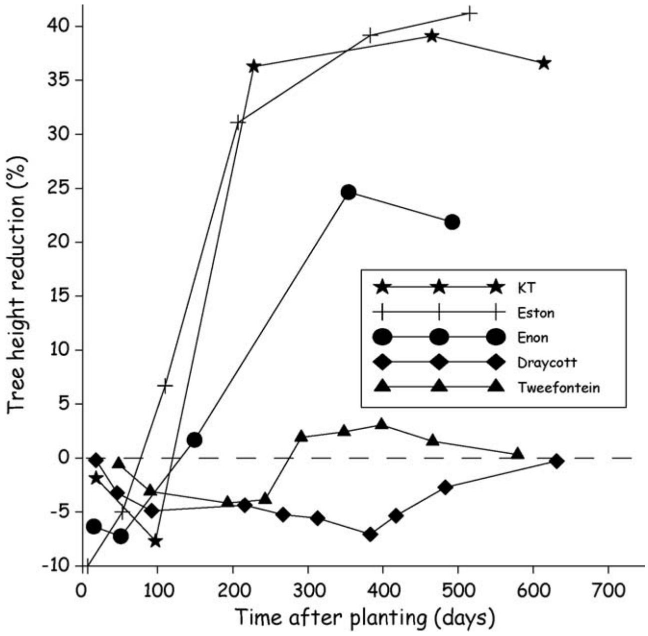

Fig. 7. Tree height reduction of the weedy control relative to the high intensity weeding treatment over time in five eucalypt vegetation management trials arranged across an altitudinal gradient in KwaZulu-Natal, South Africa. Lower altitude site: KT (65 m a.s.l.), two mid-altitude sites: Eston and Enon (878 and 1 262 m a.s.l.), and two at higher altitude sites: Draycott and Tweefontein (1469 and 1590 m a.s.l.).

Table 2
Commercial species and widely used silvicultural regimes for short-rotation hardwood crops in the summer rainfall area of South Africa.

Climatic zone	Major hardwood species	Approximate time to canopy closure (months) [level of vegetation management required][a]	Range of stand densities commonly used for short-rotation crops (stems ha^{-1} at planting and thinnings)	Fertilization at time of establishment[b]	Rotation length (years)[c]	Range in mean annual increment (m^3 ha^{-1} $year^{-1}$)[c]
Cool temperate	*E. nitens*	15+ [low]	1300–1800; unthinned	P, NP, or NPK mixtures, based on previous crop, soil type and soil organic matter levels	9–12	20–33
	E. macarthurii					14–25
Warm temperate	*E. grandis*	12–15 [moderate]	1300–1800; unthinned		8–11	20–44
	E. dunnii					19–36
	E. smithii					23–40
	A. mearnsii	12+ [intensive]	2400, with early thinning(s) to waste, down to 1500	P or PK mixtures based on geology	10–11	10–28
Sub-tropical	*E. grandis*	9–12 [intensive]	1100–1667; unthinned	N, P or NPS mixtures, based on soil organic matter levels	6–10	18–52
	Hybrids of *E. grandis*					16–57

[a] After du Toit and Dovey (2005), Little and van den Berg (2005), Viero and Little (2006), and Little (2008).
[b] After du Toit (1995), du Toit and Carlson (2000), Carlson et al. (2001), du Toit (2002) and du Toit and Oscroft (2003).
[c] After Smith et al. (2005b).

alternative (perhaps less desirable, but still widely planted) species were tested. The choice of the recommended species was based on selection criteria used for operational site: species matching (Smith et al., 2005b). For each species at each site an unimproved genetic stock was tested against improved genetic stock with the source of the unimproved material from seed collected either from local land race or of wild Australian origin. The source of the improved seed was from either first or second generation open pollinated seed orchards with forward selection. For all treatments seedlings were planted into manually prepared pits (50 cm × 50 cm × 25 cm deep) after a pre-plant chemical clearing of vegetation where necessary. Subsequent silvicultural treatments were either intensive ("high") or less intensive ("low"). Each seedling in the "high" silviculture treatments received 2 l of water and 125 g 2:3:2(22) granular fertilizer at the time of planting (du Toit, 1995) which supplies 8 g N, 12 g P and 8 g K per tree. Prerequisites for consistent and optimal benefits from fertilization are thorough weed control (Wilkinson and Neilsen, 1990; Little et al., 1997, 2003a,b) and therefore at various intervals after planting, until shortly after canopy closure, the "high" silviculture treatments were kept weed free. The "low" silviculture treatments received neither water nor fertilizer at establishment and only received every alternate weeding of the "high" silviculture treatment for the specific site. A lower planting density (1111 stems ha^{-1}), established at a planting espacement of 3 m × 3 m was compared against the conventional 1667 stems ha^{-1} established at an initial spacing of 3 m × 2 m.

Bartlett's test for homogeneity of variance of volume between sites was not satisfied and therefore no across site analysis was performed. At mid-rotation (approximately 5 years of age) productivity improvements associated with the main effects of factors were significant with a lack of interaction between these main factors. This lack of interaction between the main effects of factors has also been observed in similar studies (Little and van den Berg, 2005). The baseline control of unimproved material, established at 1111 stems ha^{-1} and low silviculture (no fertilizer and less weeding) for both species across all five trials is represented by the first vertical bar in Fig. 8 (control). The mean value for the baseline control across all trial sites is 25.3 m^3 ha^{-1} $year^{-1}$. The average magnitude of gains for the individual (and some combinations of) factors are represented by the lighter coloured vertical bars in Fig. 8. Productivity improvements associated with deploying improved genetic material averaged approximately 8% across all sites with the largest gains observed on the more productive sites and little or no gain on the lower productivity sites. Improvements associated with intensive weeding and fertilization at planting averaged 13% across all sites, and improvements associated with capturing the full potential of the site (stand density) averaged 14% across all sites. An overall improvement of 46% (MAI increase of 11.8 m^3 ha^{-1} $year^{-1}$) was achieved when all cultural factors were implemented. The relative contribution to productivity improvements, associated with the main factors has changed over time (also observed by Davidson, 1996), with the contribution of tree improvement increasing and that of silviculture displaying a reverse trend (Fig. 9).

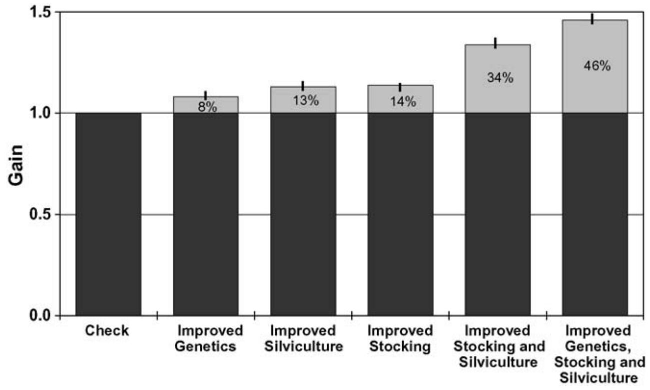

Fig. 8. Mean mid-rotation yield gains associated with tree improvement (genetics), silviculture, stocking, stocking plus silviculture, and genetics plus stocking plus silviculture (after Boreham and Pallett, 2007). Reproduced from Southern Forests 2009, 71(2):91 and used with permission of NISC (Pty) Ltd.

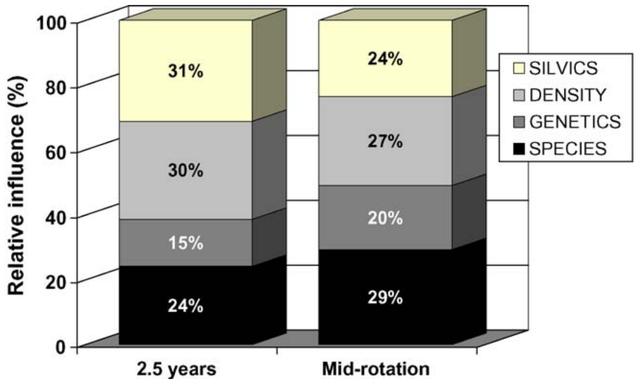

Fig. 9. Changes in relative influence to productivity gains over time for all the main factors in a *Eucalyptus* operational gain trail series (after Boreham and Pallett, 2007).

Importantly, the mid-rotation productivity improvements are additive, emphasizing the need to optimise each practice in the value chain to achieve maximum productivity. Similar results were observed by Martin and Shiver (2002) on *Pinus taeda* in the Southern USA. Improved genetic material of the appropriate species is generally being deployed at an operational level in South Africa, however, an opportunity exists to increase *Eucalyptus* productivity by practising higher levels of initial silviculture and ensuring high stocking through to rotation end.

3. Discussion and conclusions

The mechanism of the responses observed after implementation of various silvicultural treatments that improve resource availability can be summarised as follows: genetic tree improvement, hybridisation and site–genotype matching can lead to improvements in water use efficiency by trees (Dye, 2000), improved pest and disease resistance (Wingfield et al., 2008), reduced risk to adverse environmental conditions (Swain and Gardner, 2003) as well increases in the fraction of carbon allocated to stem wood (Dye, 2000). The mechanism of the response obtained to residue management, fertilization and vegetation management treatments appear to rely heavily on early improvements in the availability of nutrients and soil water which gives rise to rapid canopy development and early increases in light interception (du Toit, 2008), especially on sites with limited water availability which are common in South Africa. In addition, fertilization, residue management and vegetation management treatments usually improve stand homogeneity and reduces inter-specific competition (Little et al., 2003a,b), which could contribute to higher levels of stand productivity according to the growth dominance theory put forward by Binkley (2004). In the absence of thinning (which often increases the degree of uniformity if done from below) clonal plantings or the use of genetically improved plants may greatly contribute to stand uniformity. We hypothesize that increases in stand uniformity may contribute significantly to the gains in volume growth commonly observed in SA (this paper), Congo (Deleporte et al., 2008), Brazil (Gonçalves et al., 2008), and other regions practicing intensive silviculture.

We can conclude that the period from felling to canopy closure is indeed the most important window of opportunity to increase productivity and to ensure sustainability in unthinned, short-rotation plantations. The research findings discussed in this paper has had a pronounced impact on operational management of South African plantation forests: (1) the fact that the responses to genetic tree improvement, site–genotype matching and early, intensive silvicultural treatments are additive, underscored the need to simultaneously optimise all these factors in the value chain to achieve maximum productivity, and (2) results generally showed that site-specific silviculture (also termed site-related silviculture or precision forestry by some practitioners) is essential to realise and sustain maximum production potential (as emphasized further with specific examples below). Several tropical countries arguably have the potential to greatly improve stand productivity above current levels. For example, Nambiar and Kallio (2008) list several residue management experiments in the tropics and sub-tropics with favourable climates (e.g. MAP $>$ 2000 mm; minimal or no frost and snow risk) where stand productivities are below 15 $\text{m}^3\,\text{ha}^{-1}\,\text{a}^{-1}$. In countries where research on intensively managed short-rotation plantations is still in its infancy, emphasis should be placed on combining as many site-specific operational recommendations as possible in the silvicultural value chain.

The development of regional vegetation management standards allowed foresters to estimate the onset and severity of weed competition with reasonable accuracy, based on site altitude, previous land use and slash management (burning or residue retention). This allowed for increased precision in planning, management and budgeting.

Evidence from several series of trials in the summer rainfall area of South Africa have shown that the majority of forest soils have good to excellent physical properties that cannot be substantially (and economically) improved by soil tillage treatments. The response to soil tillage operations at establishment in South African trials are essentially due to benefits arising from improved nutrition and decreased competition. The lack of response to similar treatments under re-establishment conditions further supports this finding. A large body of evidence also demonstrates that negative impacts on soil physical properties arising from harvesting impacts (such as compaction) are strongly related to soil texture (soils with an even textural distribution being the most sensitive) and management of harvesting residue. Despite several site types being resilient, there are concerns that multiple rotations of forestry could ultimately cause a decline in soil physical properties due to soil compaction during harvesting and loss of organic carbon by occasional slash burning before establishment, particularly on the sensitive soil types. If this is the case, management intervention, by intensive land preparation, may eventually be inevitable. For example, ripping and subsoiling operations are used extensively in had setting soils of Brazil to improve stand growth (Gonçalves et al., 2004).

There are concerns that sites with low levels of nutrient reserves may eventually suffer from nutrient depletion following increasing biomass removal over time, and intensive management on short rotations, seeing that plantation land in South Africa have supported six to eight rotations of trees in some regions. The trial series on site management and productivity in tropical plantation forests (summarised by Nambiar and Kallio, 2008) have shown that stands on sandy soils with low organic matter contents (Deleporte et al., 2008; Gonçalves et al., 2008; Mendham et al., 2008) are subject to significant drops in productivity following high levels of biomass removal. This occurs as a result of depletion of nutrient pools as well as decreases in short-term nutrient availability, e.g. nitrogen mineralization rates (Mendham et al., 2008). Forest nutrient management should take congnisance of factors such as soil type, soil organic matter content, residue management (especially burning), degree of soil disturbance and environmental conditions (as modified by physiographic factors such as altitude) when formulating management and fertilizer recommendations. Some progress has been made in this area, for example to recommend specific fertilizer supplements according to tree genus, region, parent material group, soil organic matter contents, previous land use and the presence or absence of soil disturbance and slash burning. However, it is clear that this complex area of research requires an even more comprehensive, process-based understanding of nutrient dynamics and availabilities if increasingly site-specific management is to succeed.

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