

Chapter 5

Biomass Production in Intensively Managed Forests

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5.1 Introduction

Intensively managed plantations of fast-growing trees, planted on a short rotations at high stand densities, is arguably one of the most productive and energy efficient ways to produce biomass. In this chapter we discuss silvicultural options to establish and manage highly productive bio-energy plantations, based on case studies from short-rotation plantation forests in warm-climate regions. Our focus is on the growing of biomass as a main product. We also explore the energy and green house gas balances from such intensively managed systems.

A topic that has been extensively researched in short-rotation pulpwood plantations in tropical and warm-climate countries, is that of intensive management to boost stand productivity (Schönau 1984; Nambiar 2008; Stape et al. 2008, 2010; Gonçalves et al. 2007; Fox et al. 2007b; du Toit et al. 2010). This management style has been dubbed “Intensive, Site-specific Silviculture” in Southern Africa (Schönau 1984; du Toit et al. 2010), and has been responsible for large improvements in productivity. It has also been categorised under the more general field of “Precision Forestry” by some authors because the management philosophy hinges on choosing and implementing a suite of management operations that are specifically suited to the ecological capability of a specific site type, or to alleviate constraints to productivity on a specific site type (Pallett 2005; du Toit et al. 2010). This production system, with some adaptations, is arguably the most suitable starting point to design silvicultural regimes for intensively managed, highly productive biomass plantations. In its current form, it is usually a man-made (afforested) monoculture tree crop managed under a clear felling system. However, it has some important

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differences to conventional agricultural monocultures, namely minimum soil cultivation where feasible, relatively low dependence on artificial chemical inputs for sustained productivity, prolonged periods of minimal cultural interventions, a net carbon footprint that is strongly positive, and the incorporation of significant biodiversity/conservation areas for the maintenance of ecosystem services (usually in the form of ecological networks or corridors) within the broader system in the landscape (cf. Chap. 10). In Sects. 5.2, 5.3, 5.4 and 5.5, we will discuss the most important elements of “intensive, site-specific silviculture” from the existing body of knowledge which essentially consist of a number of strategic choices (e.g. choice of genetic material and planting density/rotation length combination) as well as cultural practices (e.g. site preparation, vegetation management and fertilization). We will also focus on the most promising adaptations of conventional systems that may be necessary to optimise this kind of silvicultural system for bio-energy plantations.

5.2 Matching Highly Productive Tree Taxa with Specific Site Types and Bio-energy Production Systems

There can be little doubt that the selection and genetic improvement of fast-growing tree taxa (in this context referring to species, provenances, families within provenances, hybrids or clones) have strongly boosted productivity on intensively managed plantation forests in the tropics (Zobel and Talbert 1984; Verryn 2002, 2008; Pallett and Sale 2002; Kanzler et al. 2003; Wu et al. 2007; Boreham and Pallett 2007). Particularly impressive tree breeding successes in short-rotation pulpwood plantation forestry also include improvements in properties that enhance processing (e.g. wood properties, stem form and ease of debarking – Malan and Verryn 1996; Dvorak et al. 2008) or properties that allow for better survival and productivity of a specific taxon under adverse circumstances (e.g. disease resistance, cold/drought/frost tolerance, improved water use efficiency and herbicide resistance – Hodge and Dvorak 2007; Herbert 2012; du Toit 2012; Mitchell et al. 2013). It is therefore imperative for any intensive bio-energy production system to invest in a focussed tree improvement programme that can conserve a broad genetic base of fast-growing tree families, constantly breed for resistance to newly emerging pests and diseases, and constantly improve quality of the biomass and its suitability for the particular production process. The world-wide trend in highly productive short-rotation plantation forests is to move increasingly towards planting a variety of genetically improved, vegetatively propagated hybrid clones (rather than raising seedlings from half-sib or full sib families within species), which are deployed in a mosaic of small blocks to minimise risk. Some of the more important reasons for this trend revolve around the following facts: (a) genetic gains are large and guaranteed, (b) hybrid vigour can be obtained, (c) disease resistance can be obtained through hybridisation, (d) large improvements in stand uniformity, with which comes ease of mechanisation and an increase in the partitioning to above-ground biomass (Stape et al. 2010).

Another advantage of planting clones rather than pure species of fast-growing exotics has to do with the invasive potential of some taxa when planted in a non-native environment. There is an increasing body of evidence showing that several hybrid plants are sterile or do not produce large quantities of viable seedlings (Eldridge et al. 1994; Lopez et al. 2000; Owens and Miller 2009; Chen 2010). It follows that highly bred hybrid tree clones that are less fertile or sterile can potentially be selected for planting biomass crops, so that they do not pose an invasive threat. This aspect needs further testing and experimentation, but holds promise for the establishment of “greener” bio-energy crops.

Equally important to the genetic tree improvement process that may improve stand productivity is intensive experimentation with site-taxon matching. Matching the planted taxa to site conditions is obviously important in biophysically complex landscape where climatic and edaphic conditions differ markedly in space and time. There are several examples all over the world where species/provenances or families that were not well adapted to specific climate conditions have been devastated by a single risk factor, e.g. the infection of pine species that have little resistance to *Diplodia pinea* when planted on sites that experience hailstorms (Swart et al. 1988), and the stem breakage caused in *Acacia mearnsii* and *Eucalyptus grandis* stands in the KwaZulu-Natal Midlands of South Africa following episodic, heavy snowfalls (Gardner and Swain 1996). However, new pests or diseases can easily be introduced to regions of exotic plantations, e.g. *Phytophthora pinifolia* in Chile or *Sirex noctilio* in South Africa (Tribe and Cillié 2004; Durán et al. 2008; Hurley et al. 2012). Furthermore, there are documented evidence of pests and diseases of indigenous trees that infect or attack distantly-related exotics, e.g. *Crysoptorthe austroafricana* stem canker that recently spread to infect exotic stands of *Eucalyptus grandis* stands in sub-tropical parts of South Africa (Wingfield et al. 2008). It follows that regional enterprises with fairly uniform climates (and therefore chiefly rely on just one or perhaps a few species) are at risk. In such cases, it pays to invest in research on several taxa that could potentially be suited to a site: (a) to allow for the planting a mosaic of different families/clones and so to minimise risk, (b) to have alternative taxa that can be deployed rapidly and effectively in case of the introduction of a significant pest or disease to the region, and (c) to improve site-taxon matching for lesser known taxa.

Several authors have been successful in matching species or provenances to a broader region using climatic similarities, often with a computer-aided approach, e.g. bioclimatic parameters. However, finer scale matching of taxa to specific site types require local knowledge of tree response to risk factors, as well as stand productivity and quality of biomass that can be obtained under the range of prevailing site conditions. This involves planting and testing all promising taxa across a wide range of site types in the region where it could be grown. It also presupposes that a sophisticated yet simple site classification and site evaluation system exists (e.g. Louw and Scholes 2002; Smith et al. 2005; Louw et al. 2011; Louw and Smith 2012) – sophisticated enough to take both risk factors and the drivers of resource availability to stands into account, yet simple enough to implement in practice. Information gathered from studies such as the aforementioned examples is

the only reliable foundation upon which detailed site-taxon matching can be based. Accurate site-taxon matching becomes even more important when (a) the genetic base of the planting material becomes increasingly narrow, e.g. in the sequence provenance → family → clone, and (b) when the silvicultural regime tends toward short rotations of unthinned crops. A stand consisting of a several families of half-sibs that are only moderately suited to a specific site will still contain some individuals that are well suited to the prevailing conditions, and those individuals could be the final crop trees remaining after thinning in a medium to long rotation system. This is often the case in plantation forests grown for sawtimber on 20–35 year rotations in Southern Hemisphere countries. However, if a single clone (that is not particularly well suited to the site conditions) is planted in a short, unthinned rotation, the productivity of that stand is guaranteed to be sub-optimal, and the productivity loss will be compounded over successive rotations if a coppice system is used. Furthermore, in the event of climatic extremes, an entire crop could be affected by pests or diseases, brought about by stress. It is therefore essential to have a risk profile as well as a “response surface” for the productivity potential of each important or potentially important taxon across a the broadest possible range of site types, to aid the silviculturalists in their decision making.

5.3 Selecting the Optimum Combination of Stand Density, Harvesting System and Rotation Length

Strategic planning for the most appropriate silvicultural and harvesting system for bio-energy crops should be done simultaneously for maximum economic benefit. The reasons are: (1) The profitability of plantation systems are often strongly influenced by harvesting and transport costs, the latter commonly constituting the biggest share of all expenses in the value chain from plant to mill, and (2) Different harvesting systems are designed to work optimally within specific ranges of individual tree volumes (Ackerman and Pulkki 2004), for example, (a) mechanised conventional timber harvesting with individual tree volumes from approximately 0.1 to 0.9 m³, (b) clearfelling with chainsaws from 0.01 to 0.1 m³, and (c) modified agricultural harvester <0.01 m³. We will explain this relationship with data from *Eucalyptus grandis* crops grown in South Africa, where the aforementioned volume ranges would translate into diameters at breast height (dbh) classes of approximately 16–32 cm; 8–15 cm and <8 cm, respectively. From an economic perspective, it is thus imperative to design the silvicultural system in such a way that it could deliver mature crops falling within a specific range, and to match this with the capabilities of the chosen harvesting system. To a large degree, this can be achieved by manipulating the relationship between stand density and rotation length in short-rotation crops. However, (Coetzee 1999) has shown that this relationship is strongly dependent on the site index (or similar measure of site production potential). An example of mean annual increment development in South African *E. grandis* crops,

grown on various stand densities across three different site indices are shown in Fig. 5.1, based on the data produced by Coetzee et al. 1996; Coetzee and Naicker 1998; Coetzee 1999, with key data points summarised in Table 5.1. The site index in this study is defined as the mean height of trees per compartment that fall into the 80th percentile with respect to dbh, at a reference age of 5 years (hereafter SI_5).

From Fig. 5.1 and Table 5.1, it is clear that the peak MAI on a site with $SI_5 = 26$ can be achieved (a) as early as 3.6 years with 2,000 stems ha (possibly even at 3 years if more than 2,000 sph had been tested), however, (b) it will take up to 5.0 years if only 800 stems were established per hectare. The quadratic mean dbh of scenario (a) in the aforementioned text would be 13.3 cm; while that of scenario (b) would be 19.6 cm. On a low productivity site ($SI_5 = 15.5$) the MAI will culminate at 7.0 years with 2,000 stems (scenario c) and will only culminate beyond 12 years with 800 stems per hectare (scenario d). These data sets clearly show that MAI and individual tree size are strongly related to the interactive effects of rotation length, stand density and site index. It follows that site-specific management regimes should be developed for rotation length by stand density combinations. Scenario (b) lends itself to harvesting with a mechanised system, whereas scenario's (a) and (c) are more suited to a chainsaw system. The data of Coetzee (1999) did not test very dense stocking levels, but it appears that systems with between 3,000 and 4,000 sph could yield slightly higher peak MAI's, with the volume carried on small stems which lend themselves to harvesting with a modified agricultural harvester. Sochacki et al. 2007, working on a low productivity site in Australia, showed that stand densities of up to 4,000 sph yielded the largest volume production at age 3 years in that study. Stand densities of 3,000–4,000 sph could thus be considered if harvesting with modified agricultural harvesting equipment is envisaged.

If the silviculturalist opts for very high stand densities (more than 2,000 sph) with the aim to utilise a modified agricultural harvesting system, there will be additional factors that have to be considered when deciding on the optimum stand density by rotation length combinations across a range of site indices. These considerations will include the following:

- Increased cost of establishment because more trees have to be planted
- Increased tree stress due to intraspecific competition with high stand densities (in Sochacki et al. (2007) study, tree mortality was an important factor affecting final biomass production on some treatments).
- Less flexibility around the felling age (especially on higher site indices), because productivity may decline sharply if the rotation over-matures (see Fig. 5.1).
- Early canopy closure, leading to lower weed management costs.
- Lower levels of inter-specific competition (*i.e.* between competing vegetation and trees), which will improve tree uniformity and an increasing fraction of NPP being partitioned to above-ground tissues (Little et al. 2003; Stape et al. 2010).
- Changes in wood characteristics such as density and fibre properties. Shorter rotations will have an increased proportion of juvenile wood in the final volume of biomass harvested.
- Increases in nutrient depletion from the site due to intensive biomass harvesting.

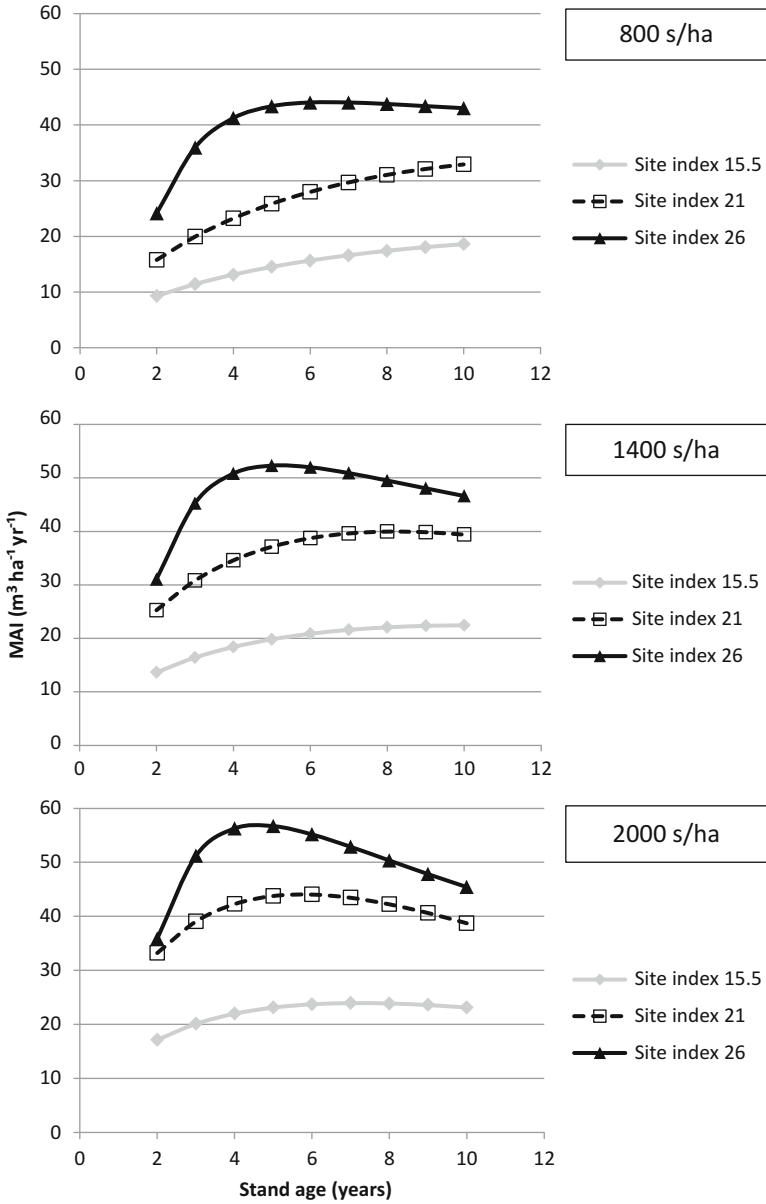


Fig. 5.1 Development of mean annual increment (MAI) in *Eucalyptus grandis* stands over time on sites with varying productivities (indicated by site indices (SI₅)) and stand densities ranging from 800 to 2,000 stems/ha (Adapted from Coetzee et al. 1996; Coetzee and Naicker 1998; Coetzee 1999)

Table 5.1 The culmination age of MAI, the actual MAI at the culmination point and the quadratic mean dbh (Qdbh) of the trees at that specific age and stand density, for the three site indices (base age 5), based on data in Fig. 5.1

Site index	800 S/ha			2,000 S/ha		
	Peak age	Peak MAI	Qdbh	Peak age	Peak MAI	Qdbh
26	5.0	44.0	19.6	3.6	57.3	13.3
21	>10	n.d.	>20	5.7	44.2	13.5
15.5	>12	n.d.	>22	7.0	24.0	12.9

5.4 Optimising Growth Conditions at Time of Establishment Through Harvest Residue (Slash) Management and Soil Tillage

Site preparation techniques (soil tillage and/or slash management) as well as harvesting impacts management aim to improve conditions for early tree and root growth by improving some or all of the following properties: soil aeration in waterlogged soils (Zwolinski et al. 2002), water infiltration, microclimatic conditions near the transplant (Carlson et al. 2004), soil nutrient mineralisation rates (du Toit and Dovey 2005; du Toit et al. 2008), or by ameliorating root growth impediments such as hard-setting soils (Gonçalves et al. 2008), semi-impenetrable or compacted layers (Smith et al. 2000, 2001) or competing vegetation (Little et al. 2001). Experimental evidence show that, where site-appropriate slash management or site preparation techniques have been applied, it had a significant impact on transplant survival and eventually on stand productivity at time of harvesting (du Toit and Dovey 2005; Gonçalves et al. 2007; du Toit et al. 2010). Conversely, the application of intensive tillage operations to situations where it did not alleviate growth-limiting situations have been shown to result in poor long-term growth responses, which, considering the high input costs, may be uneconomical (Smith et al. 2001; Lacey et al. 2001; Carlson et al. 2006; Lincoln et al. 2007). The key is thus to recognise opportunities where site preparation activities can successfully be applied and to rather implement minimum cultivation and tillage and slash conservation measures on site where the risks are high or where responses are likely to be small (Smith et al. 2000, 2001; Gonçalves et al. 2008). Some of the most important findings emanating from intensive experimentation on these issues in South Africa, Brazil, South-eastern USA and Australia are highlighted below.

When afforesting for the first time into dense native vegetation, such as grassland, it is advisable to implement intensive surface cultivation techniques, provided that the slope is not too steep and that so-called duplex soils are avoided (i.e. light textured topsoils such as sands/loamy sands with an abrupt transition to a heavy texture such as clays or silty clays). The surface cultivation eliminates the competing vegetation and stimulates an increase in nutrient mineralization after tillage, which will boost early tree growth. Basal area improvements at maturity of 11–52 % have been recorded in South Africa for a range of eucalypt stands with this treatment (Smith et al. 2000; du Toit et al. 2010).

In *re-establishment* situations, significant responses to surface cultivation are far less likely due to the beneficial effect of old root channels from previous crops, especially if soil structure or consistency does not limit root growth (Smith et al. 2001; Nambiar and Sands 1990), and the (generally) lower levels of competing vegetation that can form a dense root mat. In all these cases, minimum cultivation is recommended (Gonçalves et al. 2008). In exceptional cases, where soils have a hard-setting consistency (cohesive soils) or have suffered compaction, surface cultivation techniques such as shallow ripping could improve tree growth significantly. This approach is especially attractive likely on short rotations where drought risk in the mature phase of the crop is less likely (Gonçalves et al. 2008).

Early growth responses to deep subsoiling have been recorded on many soil types, only to diminish over time and becoming insignificant or uneconomical during drought periods or by rotation end (Smith et al. 2001; Gonçalves et al. 2008). Deep subsoiling is only economically justifiable in highly specialised situations, e.g. where inaccessible layers of soil or highly weathered saprolite can be made accessible to tree roots following subsoiling. Additional examples of inappropriate soil tillage operations are deep subsoiling operations in soils that have no macrostructure or hard-setting attributes, or excessive tillage and cultivation of duplex soils that are highly erodible. Soil quality can also be degraded by nutrient depletion (e.g. high-intensity slash burning on nutrient poor soils) or by excessive and frequent tillage of soils that will speed up mineralisation and subsequent leaching losses of soil carbon and nitrogen in young stands (Smith et al. 2001; du Toit et al. 2001, 2010) This issue is discussed more fully in Chap. 10.

Land surface modifications such as ridging and trenching can be highly beneficial where permanent or prolonged waterlogging (e.g. on flat slopes) limits root aeration and nutrient availability (Zwolinski et al. 2002; Kyle et al. 2005), especially in short rotation crops. However, this practice is certainly not suitable for moderate to well drained soils (especially those in dry climates), as it will render stands more vulnerable to drought stress.

In the preceding paragraphs, we discussed the effects of slash management operations in the inter-rotation period on nutrient supply to newly established tree stands. In very intensive biomass production systems, where most of the above ground biomass is harvested in ultra-short rotations, minimal harvest residue will remain on site. Furthermore, ultra short rotations will mean that between roughly 20 and 50 % of the stand's lifespan is spent in a pre-canopy closure state, where litterfall is nil or minimal. It follows that the forest floor will most probably be greatly reduced in size (compared to longer rotations) because litterfall inputs are lower and mineralisation rates in the semi-open canopy are usually faster due to increased temperature and water availability. An international trial series in tropical climates simulating such an intensive utilization scenario has recently been completed where harvest residue plus forest floor material was removed in certain treatments. Results showed that removal of residue plus forest floor will almost

certainly result in depressed growth of subsequent rotation(s) of trees on nutrient poor soils (Deleporte et al. 2008; Gonçalves et al. 2007; Mendham et al. 2008), but interestingly, also on sites that are nutrient rich by forestry standards (du Toit et al. 2008; Mendham et al. 2008). The reason for this seems to be not just impact of removing a certain percentage of the total nutrient pool in the system, but rather the removal of a substantial percentage of the *readily mineralizable nutrient pool* (du Toit and Dovey 2005; du Toit et al. 2008). This finding has serious implications for the long-term nutritional sustainability of biomass harvesting systems that collect all (or most of) the above-ground biomass, and will be discussed further in Chap. 10. The removal of predominantly woody material from the harvesting residue (i.e. leaving the fine twigs and foliage plus the forest floor in situ) has shown much smaller impacts and can potentially be managed sustainably with much smaller external nutrient inputs (Dovey 2012).

5.5 Intensive Cultural Management to Maximise Growth Resource Utilization

To understand the fundamental processes and mechanisms driving stand productivity, we need to introduce the so-called production ecology equation (after Landsberg and Waring 1997), which states that

$$\text{NPP} = \text{iPAR} * \alpha_c * R,$$

where

NPP = net primary production

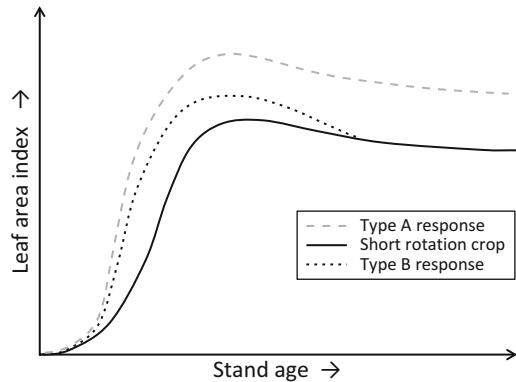
iPAR = intercepted photosynthetically absorbed radiation

α_c = canopy quantum efficiency (mol of C sequestered per mol radiation absorbed)

R = Respiration (a fairly constant value in young tree crops).

Figure 5.2 shows the theoretical development of leaf area index over time in short rotation eucalypt pulpwood crops with relatively high stand densities (after data from du Toit and Dovey 2005; du Toit et al. 2008; White et al. 2009). The three scenario's in Fig. 5.2 are: (i) low-level silvicultural inputs, (ii) intensive silvicultural inputs that temporarily improve resource availability, and (iii) Intensive site or silvicultural treatments that ensured a prolonged improvement in resource availability. The latter two responses have also been labelled as Type A (Type II) and Type B (Type I) responses (Snowdon and Waring 1984; Snowdon 2002; Rubilar et al. 2008). The areas under the curves represent the cumulative leaf area that is deployed over the rotation, which is responsible for radiation interception and hence, photosynthesis.

Fig. 5.2 Theoretical development of Leaf area index in short-rotation eucalypt crops (After du Toit and Dovey; du Toit et al. 2008; White et al. 2009). Scenario (a) is a control, scenario (b) experienced a temporary boost in resource availability and scenario (c) was subjected to a long-term improvement of growth resource availability



5.5.1 Type B Responses (a.k.a. Type I Responses)

The leaf area deployed governs the interception of solar radiation, which is pivotal in the production ecology equation presented above. The sooner that the leaf area index (LAI) can reach a peak value, the sooner optimal growth can take place because radiation interception is linearly related to biomass production (Linder 1985; Turnbull et al. 1988; Dovey 2005). In short rotations, such as bio-energy crops, the time period from planting until deployment of peak LAI may make up a substantial portion of the full rotation length, and it is thus of critical importance to minimise this period. The rapid deployment of a peak LAI is aided by high planting densities, but as described in Sect. 5.3, expensive harvesting operations also place a limit on the stand density that can be used, because of harvesting piece size constraints.

Rapid deployment of peak LAI can be achieved by intensive silvicultural management which will boost the availability of soil water and nutrients to young transplants. Management of competing vegetation and fertilization at time of establishment are two critically important operations in this regard (Little and Van Staden 2003; Wagner et al. 2006; Little et al. 2007; du Toit et al. 2010). Fertilization should be site- and crop specific to ensure best economic returns.

Hardwood stands usually have a very high demand for nutrients in the period up to and including canopy closure, e.g. Laclau et al. (2003). Research on fertilization of short-rotation *Acacia* and *Eucalyptus* tree crops in warm climates initially focussed on relatively small applications (of mainly N and P) that would boost stand productivity (Williams 1928; Beard 1952; Schönau 1983, 1984; Herbert and Schönau 1989). Fertilization at (or soon after) establishment is commonly done by commercial tree growers because of the relatively low input costs and large gains on highly weathered, P deficient sites, or alternatively, gains due to Type B responses eluded to earlier in this chapter (Barros et al. 1992, 2004; Herbert 1996; du Toit 2002; Gonçalves et al. 2008; Bennett et al. 1997; du Toit et al. 2010; Maree et al. 2012). Application rates for this type of fertilizer application usually include P at

10–40 g per tree (Gonçalves et al. 2004; du Toit et al. 2010). In specific cases, responses to additional N (0–30 g N per tree) K (0–15 g per tree) and small quantities of B has been observed (Gonçalves et al. 2004; du Toit et al. 2010). This need for N applications depends on the soil conditions (Noble and Herbert 1991) and site preparation/slash management options (du Toit and Dovey 2005; Smith and du Toit 2005; du Toit et al. 2008). Gonçalves et al. (2004, 2008), as well as Gava (1997) make the point that N and K applications are becoming more common in eucalypt plantations that have undergone several crop cycles, apparently due to increase nutrient losses in harvesting the possible depletion of readily mineralisable N.

In pine plantations, P fertilization during the establishment phase (commonly at levels between 20 and 60 kg/ha) may lead to large growth responses, but this is mainly limited to highly weathered, P deficient soils (Donald 1987; Xu et al. 1995a, b; Fox et al. 2007a; Kotze and du Toit 2012). Furthermore, pines in subtropical and warm temperate climates have generally shown the biggest responses to nutrient additions during mid or late rotation periods (12–20 years of age), when nutrient demand is much larger than supply (Donald 1987; Payn et al. 1988; Turner et al. 1996; Carlson 2000; Fox et al. 2007a; Kotze and du Toit 2012). Levels of 200–400 kg of N and 50–100 kg of P commonly give good results in mid-rotation pines. Fertilization after 12 years of age may be too late in very short rotations grown for biomass, especially if they are planted at higher stand densities. However, it appears that younger pine stands may have sufficient capacity to take up moderate nutrient applications, judging from the responses to P, K and Mg applications have been documented at time of canopy closure (age of first pruning in most stands under conventional management regimes) where acute deficiencies existed (Kotze and du Toit 2012). This finding may be of importance to short rotation pine stands that are under pressure from nutrient depletion: Economic responses can be obtained by such early fertilization efforts.

The application of hydrogels can also improve water availability during a critical period following planting (Viero and Little 2006). In addition to minimising competition, vegetation management also ensures a more homogenous crop, and this will result in the greater partitioning of NPP to above-ground biomass production, which is an added benefit.

5.5.2 Type A Responses (a.k.a. Type II Responses)

Silvicultural treatments that ensure the prolonged improvement of growth resources to tree stands usually have the greatest improvement on stand productivity, and these have been dubbed Type A effects. This happens because not only the LAI development process is accelerated, but also because of changes to the canopy quantum efficiency and carbohydrate partitioning to above-ground parts (Stape 2002; Giardina et al. 2003; du Toit 2008). Examples are: Fertilization of a nutrient deficient stand where water availability is not limiting (Giardina et al. 2003); Irrigation of a stand where water is limiting growth (Stape 2002); P fertilization

that is efficiently re-cycled and remains in the system for subsequent rotations (Snowdon 2002; Crous et al. 2007, 2008) or site preparation options improving the rooting volume accessible to trees (Zwolinski et al. 2002). The mechanism for responsible for the (usually large) Type A responses appears to revolve around an increase in canopy quantum efficiency (often accompanied by improvements in partitioning of carbohydrates to above-ground tissues), rather than a primary reliance on an accelerated LAI development, as is common in Type B responses (du Toit 2008). Where it is thus possible to implement operations that would elicit a Type A response (e.g. operations that can fundamentally change resource availability) consideration should be given to the fact that it may greatly improve stand productivity and resource use efficiency, and that these improvements are likely to recur over several future rotations. This may offset the costs of fertilizer or even the (often higher) costs of operations such as trenching, land surface modifications or subsoiling. However, as described in Sect. 5.4, conditions where intensive land preparation options are effective are limited to specific site and soil types.

5.6 Interactions Among Intensive Silvicultural Operations

The interactive effects of tree improvement, site-taxon matching, stocking, and cultural practices has been tested across five site types of different SI's on the eastern seaboard of South Africa (Boreham and Pallett 2007; du Toit et al. 2010). As a departure point, a control treatment was selected that represented many short-rotation pulpwood production stands in warm climates: A species that was well adapted to each specific site (but not the very best match possible, i.e. the second best species on that particular site), which had not undergone genetic improvement, planted at a stocking of 1,111 stems/ha with no fertilization at planting and an intermediate level of weed control. The average productivity in this experimental series could be increased by 46 % above the control treatment at 5 years of age, by using genetically improved planting stock, the best site-taxon matching, a stocking of 1,667 stems/ha and intensive weed control plus fertilization at establishment. The most important finding of this study was that, although there were no significant interactions between major factors across all sites, the response to individual factors (genetics, site-species matching, stand density, fertilization and weed control) were additive. It follows *each element* of the intensive silviculture system contributes substantially to the overall gain in productivity, and that all elements should be implemented at the higher (or more intensive) level to realise the gain that had been achieved. Bio-energy production systems should be planned to integrate all the above elements of intensive silviculture into the production system.

5.7 Intensified Silviculture, Fertilization and the Carbon Footprint

One of the main reasons for growing bio-energy plantations is a reduction of the carbon emissions whilst obtaining energy benefits. Most of the intensive silvicultural treatments needed to ensure high levels of productivity in plantations (e.g. site preparation, weeding and fertilization – see Sect. 5.5) require some energy inputs. For example, fertilizer application uses fossil fuel based energy (and is responsible for some carbon dioxide emissions) during manufacture and/or mining, transport and application. In this section we will contrast the carbon costs of fertilization and other silvicultural treatments with the potential carbon gains from increased growth in short-rotation plantations.

Energy and carbon budgets for specific scenario's in bio-energy crop systems are usually calculated through a life cycle analysis (LCA) approach, which takes account of energy inputs and outputs, as well as carbon gains and losses associated with every step of the production process. The major steps to construct carbon and energy budgets have been proposed by Schlamadinger et al. (1997) and subsequently implemented by *inter alia* Matthews (2001) Heller et al. (2003) and include:

- Definition of the system boundaries to do all calculations. A reference system is normally chosen, against which different alternative management scenario's are contrasted.
- Estimating the total energy benefits from a specific scenario (including waste products).
- Estimation of total energy inputs in the production system (including energy investments in infrastructure and energy losses along the fuel chain).
- Estimating the carbon sequestration that takes place.
- Estimating of total carbon emissions from each specific scenario.
- Estimating the net emission of other greenhouse gasses, e.g. N₂O, which can be presented as CO₂ equivalents for the purposes of the budget.

Most authors stress the importance of detailed carbon and energy budgets for every step in the LCA because changes in management regime of biomass production systems can lead to large variations in the carbon and energy budget. Mead and Pimentel (2006) make a good case to show that individual silvicultural operations should be evaluated to decide on the optimum energy production system, as their efficiencies may differ widely. In order to obtain meaningful results, these calculations will have to be done on a site-specific basis because recommendations on the type and intensity of soil preparation (Smith et al. 2000, 2001; Zwolinski et al. 2002), fertilization (du Toit et al. 2010; Kotze and du Toit 2012) and weed control (Little and Rolando 2008) differ strongly across site types.

The figures most commonly used to evaluate the suitability of bio-energy systems are:

- The energy ratio (energy produced per unit of energy input)
- Net energy yield (energy output minus energy input per hectare)
- The carbon emission coefficient (inclusive of the greenhouse gas emissions expressed as CO₂ equivalents)

Despite the strong dependence of the carbon and energy balance on individual cultural practices when applied to specific site types, a few useful generalisations can be made: Energy ratio's of forestry crops (in temperate climates) typically vary between 10 and 25, compared with annual crops that vary between 1 and 5 (Mead and Pimentel 2006). Energy ratio's as high as 55 have been reported for temperate climate forest crop systems under intensive management and fertilization (Heller et al. 2003). Energy ratio's of 42 have been calculated for warm climate eucalypt crops in semi-arid areas (Wu et al. 2007) and ratio's in excess of 60 have been estimated for a hypothetical *Pinus taeda* and *Eucalyptus grandis* systems that included site preparation and fertilization inputs (Mead and Pimentel 2006). The three warm-climate case studies have all shown considerable room for improvement of the energy ratio if specific vegetation management, harvesting and/or transport regimes are adopted. New research should focus on the ability of warm climate tree crops across different site qualities to produce energy efficient biomass through appropriate silvicultural management strategies.

5.8 Harvesting Larger Percentages of Biomass from the Stand Than Conventional Practices

Biomass procurement per unit of land area can obviously be increase if whole tree harvesting is practised, rather than stem wood harvesting only. However, this relatively small increase in harvestable biomass per hectare comes with a relatively large export of nutrients. Several authors have constructed equations whereby bark, branch, and leaf mass and nutrient contents can be estimated from stem mass or volume, for example Dovey (2009). These tools are useful when calculating the additional nutrient export when the harvesting of additional biomass is considered. Increasingly intensive silviculture and frequent harvesting of ultra-short rotations may result in a net loss of nutrients in many plantations. Recent work in intensively managed short-rotation plantations has shown that fairly large nutrient losses of several elements may occur, which are seldom compensated for by increased inputs (through atmospheric deposition or fertilization). Nutrient losses and gains, as well as the long-term nutritional sustainability of short rotation forestry systems are discussed in detail with some case study data sets in Chap. 10.

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