20 Pines

C. Dana Nelson,[1] Gary F. Peter,[2] Steven E. McKeand,[3] Eric J. Jokela,[2] Robert B. Rummer,[4] Leslie H. Groom[5] and Kurt H. Johnsen[6]

[1]*USDA Forest Service, Southern Research Station, Southern Institute of Forest Genetics, Mississippi, USA;* [2]*School of Forest Resources and Conservation, University of Florida, USA;* [3]*Department of Forestry and Environmental Resources, North Carolina State University, USA;* [4]*USDA Forest Service, Southern Research Station, Alabama, USA;* [5]*USDA Forest Service, Southern Research Station, Louisiana, USA;* [6]*USDA Forest Service, Southern Research Station, North Carolina, USA*

20.1 Introduction

The southern pines (yellow or hard pines, genus *Pinus*, subgenus *Pinus*, section *Pinus*, subsection *Australes*) occupy an immense land-base in the south-eastern region of the USA (Little and Critchfield, 1969). In addition, they are planted and managed for wood production on millions of hectares worldwide, including in China, Brazil, Argentina and Australia. The taxonomic subsection *Australes* consists of 11 species, ranging from relatively minor to major in terms of land base occupied and management opportunities. For example, Table-mountain pine (*Pinus pungens*) sporadically occupies higher elevation sites in the southern Appalachian Mountains and due to declining habitat is considered a species of concern for conservation (Erickson *et al*., 2012). In contrast, loblolly pine (*Pinus taeda*) has a large native range in the USA with an even larger managed land-base (across the lower and upper Coastal Plains and the Piedmont physiographic region) as a result of extensive planting and intensive silviculture in response to the wood products industry. In addition to loblolly pine, three other southern pine species are considered major due to their large native ranges in the USA: shortleaf pine (*Pinus echinata*), longleaf pine (*Pinus palustris*) and slash pine (*Pinus elliottii* var. *elliottii*). Of note, the former two are also considered to be species of concern for conservation (Erickson *et al*., 2012) due to long-standing land management practices that have favoured loblolly pine. Similarly to loblolly pine, although on a smaller scale, slash pine has been widely planted and managed for wood and fibre production. Because of this, slash pine could be an important component of southern pine production for bioenergy purposes, sharing many similar features in this respect to loblolly pine. However, for the purpose of this chapter we will focus our discussion on loblolly pine and consider the general features and properties in bioenergy production, genetics and breeding for bioenergy traits, silvicultural practices for bioenergy production, tree harvesting and chip processing, bioenergy opportunities and challenges, and sustainability of bioenergy production systems. Socio-economic analyses and their implications are critical for the whole system but are beyond the scope of this chapter.

20.2 Southern Pines in Bioenergy Production

With the implementation of global carbon reduction goals, concerns over the stability of supply and cost of crude oil, renewable forms of energy from biomass have received significant increases in commercial interest. In 2007, the US federal government passed the Energy Independence and Security Act, which raised the renewable fuel standard (RFS). The RFS now calls for 36 billion gallons of renewable fuels, 21 billion of which are required to be obtained from cellulosic ethanol and other biofuels, by 2022. In addition, the law requires that the renewable fuels be produced with at least 20% lower life cycle greenhouse gas emissions relative to gasoline and diesel from crude oil. Current US production of cellulosic based biofuels is still in its infancy with a number of companies, including Abengoa in Kansas, BlueFire and KiOR in Mississippi, Dupont in Iowa, GEVO in Minnesota, Mascoma in Michigan, POET in Iowa and ZeaChem in Oregon, building or planning to build intermediate scale facilities. This indicates indicating that additional feedstocks will be required including forest trees such as the southern pines, both as purpose-grown crops and residues from other harvest operations.

The southern pines are a proven sustainable source of biomass for renewable chemicals, materials and bioenergy. They grow on over 37 Mha in the southern USA and supply ~18% of the global supply of industrial roundwood (Prestemon and Abt, 2002). The US forest products industry already generates 77% of all industrial biomass energy by burning wood waste and lignin at high thermal efficiencies in wood processing facilities. Even though southern US forests produce more industrial roundwood than any other single country, annual wood growth exceeds harvest rates. An important reason growth exceeds removals is the more than tenfold greater productivity of planted compared with naturally regenerated pines (Fox *et al.*, 2007). In the region, there are 13 Mha of loblolly and slash pine plantations, and nutrients and competition are managed to substantially increase yields (Conner and Hartsell, 2002; Munsell and Fox, 2010). Since the mid-1980s, virtually all of these plantations have been established with genetically improved planting stock.

Commercial interest in using southern pine for bioenergy and biofuel production is strong because key questions related to scale, cost and sustainable supplies are readily answered. An extensive, robust supply chain for roundwood has been developed for the pulp and paper industry, and this supply chain operates year round. Excellent inventories of available standing biomass and reliable predictions of yield for planted pines enable siting of facilities at locations with adequate immediate and future supplies of biomass. Because harvests of the higher density woody (i.e. lignocellulosic) pine biomass can occur year round, the logistics of using wood for bioenergy and biofuel are simpler than perennial grasses and crop residues that need to be compressed and stored. Production, harvesting and transportation costs are understood, and delivered southern pine wood costs have been more stable than other agricultural commodities. Finally, net energy yields from southern pine to ethanol are estimated to be higher than maize starch, cane sugar and sweet sorghum (Evans and Cohen, 2009). This higher net energy is due to the substantially lower energy inputs used in growing, harvesting and transporting planted pine compared with herbaceous grass crops and the higher energy obtained from lignin. Thus, overall southern pines are a very attractive immediate and future source of biomass for bioenergy production.

The expansive and productive southern pine forests have attracted substantial new interest as a source of biomass for standalone facilities to produce bioenergy and biofuel. For example, five large commercial facilities that produce wood pellets for biopower have been built, and a number of woody biomass to electrical power or biofuel facilities are planned or are being built in the region. Compared with biopower, production of biofuels from lignocellulosic biomass is more complex and technically challenging, in part because cost and environmental metrics will need to be met simultaneously. The central technical challenge for converting lignocellulosic biomass to liquid fuel is that sugars, which account for the majority of the carbon, have high oxygen content whereas fuels are carbon rich and have no or very low oxygen content. Currently a large number of approaches, broadly categorized into biochemical and thermochemical methods to convert lignocellulosic biomass to biofuels, are being researched and developed. Several of the most promising approaches and their potential for implementation with the southern pines are discussed below in detail.

Clearly, the issue of sustainability of southern pine energy-wood (i.e. stemwood and/or residues harvested for bioenergy uses) production systems needs careful consideration, in particular the implications of whole-tree harvesting on shorter rotations. Can sites continue producing biomass at the same or increasing levels over multiple rotations? Can sites continue to provide ecosystem services at socially and culturally acceptable levels? Over the last several decades, the regions' forestry sector has gained much insight into these questions through silviculture research and land management experience, and the answers seem favourable for sustainable energy-wood production. However, bioenergy policy affecting economic and regulatory considerations will require continued monitoring and study of their impact on sustainability issues.

20.3 Genetics and Breeding for Bioenergy Traits

In recent years, about 1 billion loblolly and slash pine seedlings have been planted each year in the US south, and virtually every one of these seedlings has come from intensive tree-breeding programmes (McKeand *et al.*, 2003). The cooperative tree improvement programmes in the southern USA have been responsible for the vast majority of tree breeding with southern pines for the last 50+ years. These cooperative programmes are: the Cooperative Forest Genetics Research Program (CFGRP) at the University of Florida (http://www.sfrc.ufl.edu/cfgrp), the NC State University Cooperative Tree Improvement Program (http://treeimprovement.org) and the Western Gulf Forest Tree Improvement Program at the Texas Forest Service and Texas A&M University (http://www.ars-grin.gov/misc/wgftip).

Breeding strategies have emphasized population improvement for broad adaptability and value improvement. The traits of interest for improvement have been volume production, stem straightness, and resistance to fusiform rust (caused by the fungus *Cronartium quercuum* f. sp. *fusiforme*). In some programmes, wood density has been modified, but relatively little effort has been focused on changing wood properties in most populations. The focus on volume and stem quality versus wood properties is in large part a function of the wood market in the southern USA. Currently, landowners realize most of their financial benefit when saw-timber and poles are harvested as compared to pulpwood, so most breeding and deployment emphasis has been on growth and stem quality traits, and value improvements have been impressive (Vergara *et al.*, 2004, 2007; McKeand *et al.*, 2006a). Thus, pine breeders will continue emphasis on selecting high-yielding varieties that grow across a range of different sites, which will have positive impacts on energy yields per hectare per year.

The harvest index of southern pine plantations is already high, and for energy-wood plantings is expected to be higher as whole trees are likely to be harvested to maximize biomass yields and reduce harvesting costs. Given this possibility, altering carbon allocation between stems and branches may be of limited value, whereas increasing carbon allocation to the stem over roots could improve biomass yields. Little is known about the genetic control of allocation between shoots and roots in southern pine, but it is clear that fertilization significantly increases total carbon accumulation in shoots and roots (Retzlaff *et al.*, 2001). Biomass yield is also influenced by wood density; consequently increasing juvenile wood density in fast-growing pine trees offers the potential for raising yields in energy-wood plantations. However, achieving increases in wood density could be difficult by traditional breeding and selection in some populations, because of the negative genetic correlation between wood density and growth (e.g. McKinley *et al.*, 1982; Belonger *et al.*, 1996; Atwood *et al.*, 2002). It may be possible to increase wood density and growth simultaneously through traditional breeding in many populations where the traits are independent, or there is a negligible correlation (Zobel and van Buijtenen, 1989; Gräns, 2012).

In addition to improving biomass yield, breeding for wood properties can also enhance bioenergy yields from southern pine. For example, in extractive free wood, the heating value is linearly correlated with Klason lignin content, increasing by ~1% for each 1% increase in lignin content (White, 1987). Research demonstrates that wood chemical composition is under weak to moderate genetic control, and substantial genetic variation exists for selecting germplasm with altered wood properties (Sykes *et al.*, 2006). Natural and breeding populations of southern pine have wood lignin contents that range from 25 to 35%, thus the heating value of extractive free wood can differ by as much as 10% (G.F. Peter, unpublished). With biochemical methods for conversion to liquid fuels, the chemical composition and structure of the lignocellulosic biomass dramatically affects the efficiency of saccharification and fermentation and total yield of available sugars (Himmel *et al.*, 2006). Thus, identifying varieties with low and high lignin should both increase energy and fuel yields, depending on the conversion technology. The limited evidence available suggests that wood chemistry is not genetically correlated with growth, as has been reported for angiosperm (i.e. hardwood) trees (Novaes *et al.*, 2010).

In addition to breeding, genetic engineering provides an important alternative approach for altering wood chemical properties for bioenergy and biofuels. The pathways for synthesis of all major wood chemicals, including cellulose, galactoglucomannan, arabinoglucuronoxylan, lignin, lipids, sterols and terpenes are largely conserved with other land plants. For example, in loblolly pine, the three isoforms of the catalytic subunits of cellulose synthase involved in secondary wall synthesis in xylem are well conserved with woody and herbaceous angiosperm species (Nairn and Haselkorn, 2005). Enzymes in the pathway that catalyse synthesis of coniferyl alcohol from phenylalanine are well conserved with those in angiosperms (Peter and Neale, 2004). Pines synthesize and accumulate mono- and diterpenes in the wood via the conserved 2-C-methyl-D-erythritol 4-phosphate/1-deoxy-D-xylulose 5-phosphate pathway (Zulak and Bohlmann, 2010), suggesting that fundamental knowledge from angiosperm plants can be applied to genetic engineering of wood chemical composition in pine. For example, introducing two genes that mediate syringyl alcohol synthesis in angiosperms into pine should lead to syringyl lignin formation (Li *et al.*, 2003).

In angiosperms, syringyl lignin is more readily extracted during pulping and *Populus* trees with more syringyl relative to guaiacyl lignin saccharify better, requiring milder pretreatment (Studer *et al.*, 2011). Large increases in wood heating value can be achieved by increasing wood extractive content. Extractives are composed of lipids, fatty acids, sterols and terpenes, all hydrocarbon-rich compounds with similar heating values as crude oil. Loblolly and slash pine synthesize and accumulate substantial amounts of terpenes; in mature trees these can be up to 20% of the dry weight of wood (Stubbs *et al.*, 1984). Thus, increasing wood terpene content in trees grown for short rotations will also increase energy yields per hectare per year. While pine terpenes are valuable chemicals and have been recovered at commercial scales for a long time, the interest for liquid fuel production is new. For example, pinenes can be efficiently dimerized to produce a compound with similar properties as jet fuel from petroleum (Harvey *et al.*, 2010). Thus, altering wood properties offers an excellent opportunity to improve energy yields by improving conversion efficiencies.

An important question is whether energy-wood markets will value these traits sufficiently to justify these efforts given the long generation intervals and rotation times for pines. Breeding for these additional traits requires economic justification. If more traits are included in a selection and breeding programme, a reduction in genetic gain will occur in other traits. For example, if higher wood density is desired and is given the same weight as volume in a selection index, then the potential gain in volume is reduced in half assuming the two traits are independent. If there is a negative correlation, then reduction in volume would be greater than 50%, suggesting that genetic engineering approaches may be favoured for altering wood property traits in pine clonal varieties optimized for energy-wood yield for bioenergy production.

The most likely scenario, at least in the short run, for genetics having an impact on bioenergy production is that specific existing families or clonal varieties with desirable wood properties will be identified by researchers, and these genotypes can be operationally deployed or selectively harvested if they have already been planted. In current deployment populations, there are hundreds of different families that could be screened and utilized immediately (McKeand *et al*., 2003). Even though the parents of these families have been highly selected for growth, stem quality and disease resistance, there will assuredly be high degrees of genetic variation for almost any wood-property trait. Breeders can screen families in deployment populations for desired traits, and if there are economic incentives for landowners to plant them, these families will be utilized (Byram *et al*., 2005; Peter *et al*., 2007). An additional option could develop for landowners if valuable varieties of loblolly or slash pines are identified. Ten years ago, 59% of the loblolly pine plantations and 43% of the slash pine plantations were established as single-family blocks (McKeand *et al*., 2003); these percentages are substantially higher (perhaps up to 80% for both species) today. Most large landowners know the genetic identity of their plantations, so if valuable varieties are found, selective harvest of these varieties would be possible.

Loblolly and slash pine are essentially undomesticated species, having been through only three cycles of selection and breeding, and large increases in tree growth are still obtainable through traditional breeding methods. These gains in growth will likely be achieved much faster with implementation of molecular marker-based selection (Nelson and Johnsen, 2008; Resende *et al*., 2012; Zapata-Valenzuela *et al*., 2012). The likelihood of utilizing genetic differences in bioenergy traits in southern pines will depend more on economic and market forces rather than genetic factors. If traits are economically important, then breeders and tree-improvement foresters will take advantage of the information to breed, engineer and deploy specific varieties for energy-wood plantations.

20.4 Silvicultural Practices for Bioenergy Production

20.4.1 Site selection

Of the southern pines, loblolly has the most extensive natural and managed range and, therefore, site selection is critical relative to evaluating its performance and suitability as a biofuel species. It can be found growing in a variety of habitats that vary based on physiography, geology, soils and climate. Throughout its natural range, loblolly pine occurs within multiple physiographic regions such as the Coastal Plain (Atlantic and Gulf), Piedmont, Ozark Plateaus and Quachita Mountains, Ridge and Valley, and the Appalachian and Interior Low Plateaus (Morris and Campbell, 1991; Schultz, 1997). Major soil orders among these regions include: Alfisols, Entisols, Histosols, Inceptisols, Mollisols, Spodosols and Ultisols.

Site classification systems used across the southern USA for species deployment decisions tend to be multi-faceted and include elements related to soil type (e.g. series, drainage class, depth and characteristics of the subsoil–argillic horizon), site quality (actual and potential), climate and disease hazard rating (e.g. fusiform rust). As loblolly pine tends to be a nutrient-demanding species compared to other southern pines, it grows best on high quality sites (soils) that are fertile, moderately acidic, have imperfect to poor surface drainage, a thick medium-textured surface layer and fine-textured subsoil. Poorest growth is often associated with shallow, eroded, or very wet or waterlogged soils.

The Coastal Plain region accounts for the majority (75%) of the managed loblolly pine plantations (Shultz, 1997). This physiographic region is subdivided into the lower, middle and upper Coastal Plain and the topography can vary from level to gently rolling to hilly and undulating. As such, the soils can range from very poorly to excessively drained and also differ markedly in fertility based on drainage class, soil texture, parent materials and historical land use patterns.

Soil groupings, based on easily recognizable features, have been used successfully in the southern USA by foresters and natural resource specialists to identify sites where available nutrient supplies are low, or where other site factors (e.g. moisture availability) influence growth and species performance. To understand the general distribution of forest soils and their fertility in the region, it may be helpful to consider the major land areas of the Coastal Plain region, and a soil classification system developed in the 1980s by the Cooperative Research in Forest Fertilization (CRIFF) programme at the University of Florida (Fisher, 1981; Fig. 20.1). The eight CRIFF soil groups (A–H) are defined using drainage, texture and depth of the subsurface soil horizons. Table 20.1 defines the nature of each soil group in relation to the major land areas.

The CRIFF soil classification system is still widely used today as a basis for stratifying forestland for species deployment decisions (Fox, 2004; Fig. 20.2) and prescribing silvicultural treatments. Suitable sites for loblolly pine plantations are commonly found on CRIFF A, B, C, E and F group soils (Fig. 20.1 and Fig. 20.2). For example, wet mineral flats in the lower Coastal Plain are characterized as poorly to very poorly drained, fine-textured soils that developed from slack-water deposits (e.g. CRIFF A; Paleaquults, Haplaquults). An argillic (Bt) horizon commonly occurs at depths less than 50 cm. These soils are inherently phosphorus deficient, but can produce some of the most productive stands of loblolly pine when bedded and fertilized. Similarly, Coastal Plain flatwoods sites found in northern Florida and southern Georgia are typified by poorly to somewhat poorly drained soils that developed from coarse-textured marine sands (e.g. CRIFF C; Alaquods, Haplaquods). Loblolly pine tends to grow best on those soils having well-developed clayey (argillic) subsoil, especially when combined with silvicultural treatments that alleviate nutrient deficiencies. In the upper Coastal Plain and Piedmont regions, where topographic relief has contributed to a fairly dissected and eroded landscape, loblolly pine growth rates can range from fair to excellent. As most soils in this region (CRIFF E and F groups) were once farmed for cotton,

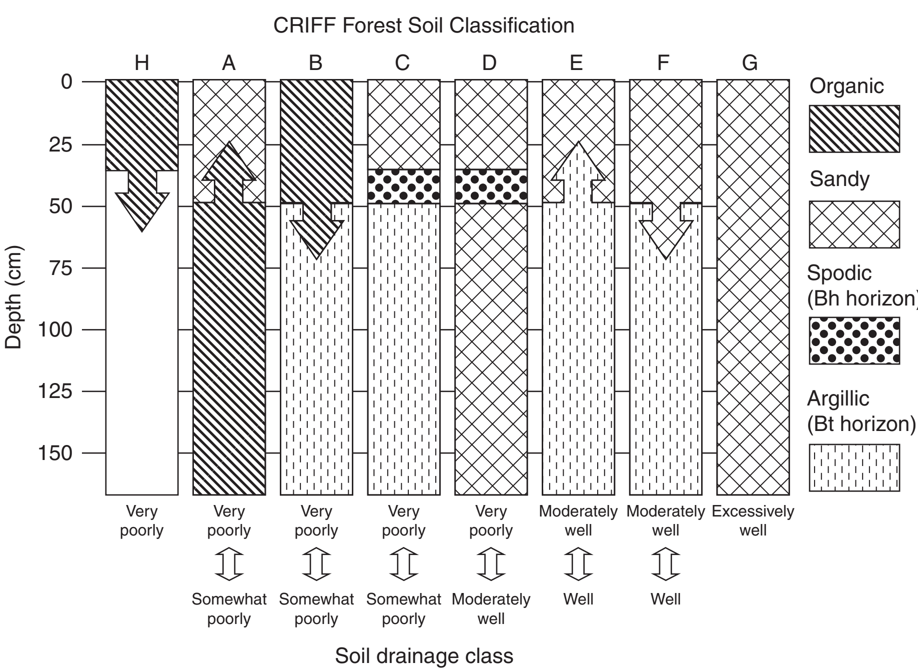


Fig. 20.1. Cooperative Research in Forest Fertilization (CRIFF) soil groups for the southern USA (adapted from Jokela *et al.*, 1991a).

Table 20.1. Definitions of CRIFF soil groups within the Coastal Plain region of the southern USA.

CRIFF soil group	Major land area	Soil drainage class	Important features
A	Savannahs	Very poor to somewhat poor	Sand to loamy sand surface layer less than 50 cm thick, with a finer textured soil (argillic) horizon below
B	Savannahs	Very poor to somewhat poor	Sand to loamy sand surface layer greater than 50 cm thick, with a finer textured soil horizon (argillic) below
C	Flatwoods	Poor to somewhat poor	Spodic horizon below the surface layer. Sandy loam or finer textured soil horizon (argillic) below the spodic horizon
D	Flatwoods	Poor to somewhat poor	Spodic horizon below the surface layer. Sand to loamy sand soil horizon below the spodic horizon (no argillic horizon)
E	Uplands	Moderate to well	Sand to loamy sand surface layer less than 50 cm thick, with a finer textured soil horizon (argillic) below
F	Uplands	Moderate to well	Sand to loamy sand surface layer greater than 50 cm thick, with a finer textured soil horizon (argillic) below
G	Sandhills	Excessive	Sand to loamy sand surface layer at least 100 cm thick (no argillic horizon)
H	Depressions	Very poor	High in decomposing plant residues, often an organic soil

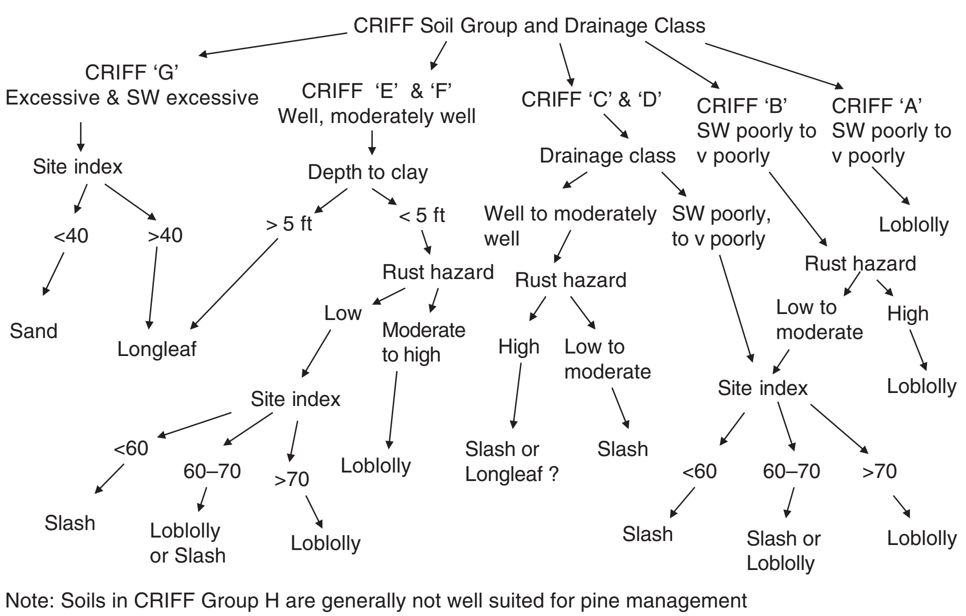


Fig. 20.2. Species deployment decision key for southern pines in the Coastal Plain of Georgia, Florida and Alabama (from Fox, 2004). SW, somewhat.

erosion processes have led to losses of the fertile topsoil, resulting in exposure of subsoil horizons that have lower fertility and higher mechanical resistance to root penetration and development. Conversely, many loblolly pine stands in this region have benefitted from the 'old-field' effect, where residual soil fertility levels that resulted from recent or former agricultural practices have contributed to highly productive stands of loblolly pine.

Site quality, expressed as site index (i.e. average height of dominant and co-dominant trees at index age of 25 years), can be variable both among and within soil groups, as well as physiographic regions. Research has clearly demonstrated that site quality is not a 'fixed' attribute, but can be modified with site-specific silvicultural treatments (Munsell and Fox, 2010). For example, Jokela *et al*. (2010) reported that site index for loblolly pine growing on a somewhat poorly drained Ultic Alaquod (CRIFF C group soil) in northern Florida increased from 22.5 to 26.5 m when fertilizer and understorey competition control treatments were prescribed. These changes in site index were also expressed in volume yields at 25 years, with the treated stands having 2.2-fold more standing volume than the untreated controls (367 versus 165 m^3 ha^{-1}). With today's genetics and silvicultural technologies, it is possible on some sites to achieve site index levels of about 30 m.

20.4.2 Site preparation

Mechanical treatments

The successful establishment of loblolly pine stands for energy-wood production will require some form of site preparation, be it mechanical (e.g. bedding, shearing, spot raking, subsoiling, disking, combination ploughing) or chemical (herbicides). Prescribed fire may also be used. The choice of site preparation methods depends on many factors, including: management objective, physiographic region, past management practices, harvesting method, soil characteristics, site quality, understorey competition levels, tract size, special needs considerations and economics. For stand establishment, some combination of treatments will be used to facilitate the control of understorey competition levels, reduce harvest debris (slash) that impedes planting operations, improve surface soil drainage on problematic sites and ameliorate soil physical properties (e.g. reduce surface soil compaction (skid trails and ramp areas) and soil strength). The collective impact of these site preparation treatments can increase future harvest yields, reduce rotation lengths and increase economic returns to the landowner by improving seedling survival, altering site resource availability (e.g. through competition control) and encouraging greater root development for water and nutrient uptake (Morris and Lowery, 1988; Allen *et al*., 1990; Lowery and Gjerstad, 1991).

Following the harvest of a previously established loblolly pine plantation, non-marketable stems may be sheared and the residual logging slash (branches, foliage, roots, stumps) spot-raked into small piles to facilitate other site preparation activities and future planting operations. The amount of logging slash left on site can vary, but estimates from Mississippi suggest an average of about 34.5 dry t ha^{-1} (Schultz, 1997). Bentley and Johnson (2008) examined logging utilization on softwood harvests in Alabama and estimated that about 12% of total softwood volume was left behind as logging residues. These slash piles may be left in place, burned, or alternatively chipped on site and collected when managing for biofuels production. Regardless, careful supervision of the raking/collection operation is warranted to avoid displacement of surface soil into the piles and the possible subsequent reductions in future site productivity (Morris *et al*., 1983).

On poorly and very poorly drained soils, characteristic of many lower Coastal Plain sites, bedding is commonly used to increase pine survival and growth because high water tables lead to anaerobic conditions. Gent *et al*. (1986), for example, reported that bedding increased height growth by 1 to 3 m. Bedding is also a form of surface soil tillage that mixes organic debris (forest floor) into the mineral soil, which can lead to increased rates of N and P mineralization (nutrient supply) and reduce levels of woody competition. Single- or double-pass bedding operations may be used depending upon the site, with the first pass commonly conducted in the spring and the second bed pass conducted in mid- to late summer. Typically, the beds will need to settle before planting to avoid having seedling root contact with unsettled air pockets, which can lead to increased mortality. Contour bedding is also essential on sites with slopes to reduce the risks of erosion and sediment transport. As is the case with any silvicultural operation, including site preparation activities, users are encouraged to follow the best management practices (BMPs) guidelines for their state (an example BMPs document for the state of Florida can be found at: http://www.floridaforestservice.com/publications/silvicultural_bmp_manual2011.pdf).

Other mechanical site preparation treatments used prior to planting may include roller drum chopping, disking and subsoiling. Chopping breaks up existing woody vegetation and crushes the logging slash into smaller pieces to enhance burning and the decomposition process. It does little, however, to control the development of re-invading woody and herbaceous competition, and is less frequently used today than in the past. Subsoiling may be used on soils having high mechanical resistance (strength) or on soils with cemented horizons that reduce root penetration and effective occupancy of the lower solum.

Chemical treatments

The use of chemical site preparation continues to grow as a cost-effective tool for establishing southern pine plantations. The primary purpose of this treatment is to reduce sprouting and re-establishment of woody and herbaceous forms of competition and to increase pine growth. Today, the availability and efficacy of both foliar and soil active compounds (including generic formulations), coupled with a competitive cost structure and resultant growth benefits to the pines, have made their use commonplace, either singly or in combination with other mechanical site preparation (e.g. bedding) techniques.

The selection of herbicides to be used for site preparation will be dependent on the suite of species to be controlled, soil conditions (texture), costs and site-specific factors related to environmental sensitivity and health and safety (Nelson and Cantrell, 2002). Common site preparation herbicides (pre-plant) for loblolly pine plantations include: glyphosate, hexazinone, imazapyr, triclopyr and metsulfuron. Tank mixes that combine chemicals are commonly used to increase treatment efficacy. Application methods for chemical site preparation vary and may include broadcast or banded applications using tractors/skidders mounted with boom or boomless sprayers, aerial systems, basal stem treatments, cut stump applications, hack and squirt (cut stem) treatments and backpacked foliar sprays.

The US Environmental Protection Agency, responsible for registering all herbicides, classifies them as general or restricted-use. In the latter case, purchase and use requires a certified, licensed applicator. For some compounds (e.g. triclopyr), a wait period may be necessary before planting occurs to avoid mortality losses. Users are encouraged to consult both a professional applicator and the herbicide label for determining the appropriate rates, carrier (e.g. water, oil), volume of spray per hectare, timing, and health and safety concerns. For example, on upland sites a late summer/early autumn application of glyphosate and imazapyr (Chopper®) may be used for broad spectrum control, whereas imazapyr and triclopyr (Garlon®) may be more efficacious on lower Coastal Plain flatwoods sites that contain gallberry (*Ilex glabra*) and saw-palmetto (*Serenoa repens*).

Depending upon the degree of competition control at establishment and the growth rates of the pines, additional herbicide (pine release) treatments may be required during the first 2 to 5 years. Common pine release herbicides may include, among others, imazapyr, hexazinone, sulfometuron methyl and glyphosate. Broadcast and banded applications are commonly conducted, depending upon the herbicide being used and site-specific factors. Tank mixes may also be used to increase the effectiveness of the treatments. In a regional experiment conducted across the southern USA, that included a common study design, Miller *et al.* (1991) examined and compared loblolly pine growth responses across 14 sites to four types of competition control (total control, herbaceous control only, woody control only and no control). After the first 5 years, diameter growth was more responsive than height to the treatments. For example, pine volume associated with the total control treatment was fourfold greater than the no control treatment. The results suggested that herbaceous competition control during the early stages of stand development was critical, with stand volumes being increased on average by 171% across sites compared to 67% with woody control. Subsequent research has also demonstrated that woody competition can become a significant factor decreasing pine growth in older stands (Miller *et al.*, 2003).

20.4.3 Planting stock and initial spacing

Loblolly pine stands being managed for a biofuels objective will generally utilize the same types of planting stock as those used for meeting traditional forestry objectives. The vast majority of seedlings planted will be of bare-root origin (1-0 stock, i.e. 1 year in the seedbed and 0 years in the transplant bed) that are genetically improved (as discussed earlier) for growth, form, disease resistance (e.g. fusiform rust, pitch canker), or possibly chemical composition. Containerized seedlings may also be used in special cases, but they are about twice as expensive as bare-root stock. In general, as the level of genetic improvement increases (e.g. open-pollinated, control-pollinated, clonal varieties) so too does the cost of seedlings. Care must be exercised when selecting the proper planting stock for a site. For example, on sites having a high fusiform rust hazard rating, deployment of fusiform rust-resistant seedlings are recommended as they will decrease the likelihood of associated mortality and growth losses. By comparison, on low rust-hazard sites, seedlings that are genetically improved for growth may be preferentially selected as they can significantly increase biomass yields. Seedling deployment decisions, therefore, should consider the trade-offs between genetic improvement for disease resistance versus growth (e.g. Vergara *et al.*, 2007).

Proper care of seedlings (lifting, storing and transporting), optimal planting season and weather conditions are central elements necessary for establishing a successful loblolly pine stand (Wakeley, 1954, 1969; Harrington and Howell, 1998). Seedlings should be transported from the nursery to the planting site in refrigerated vans that maintain proper temperature and humidity. Most guidelines used to 'time' the planting operations in the southern USA concentrate on the period between early November and mid-February. Several southern states also use a weather classification system based on temperature, relative humidity and wind speed to determine normal, marginal and critical planting conditions (Long, 1991). Both machine- and hand-planting operations are used with loblolly pine, and the choice is often based on topography, residual harvesting debris, physiographic region, prior experience and costs. For example, hand planting may be preferable on steep slopes and those sites with broken topography, whereas machine planting may be used on gentle slopes and 'clean' sites that will not result in a poor planting job with a high rate of skips. Survival surveys are normally conducted after the first growing season, as seedling losses and stand failure will likely occur at that time (Matney and Hodges, 1991). Seedling failures are not common, but must be addressed early in the life of the stand to avoid yield reductions. Growth and yield simulation models, coupled with financial analyses, provide a more realistic basis for evaluating the trade-offs associated with mortality losses than establishing an arbitrary number of seedlings surviving per unit area (Matney and Hodges, 1991).

Decisions on initial planting density will vary depending upon ownership objectives. Some landowners may prefer to establish stands with a dedicated biofuels objective, while others may choose an initial planting density that produces a mixture of traditional forest products (pulpwood, chip-n-saw, sawtimber), including biomass. Stands planted at close spacings tend to produce more total biomass, but the yields are distributed over smaller diameter trees that have less value. For example, Zhao *et al.* (2012) reported stand-level biomass accumulation for loblolly pine grown in a region-wide culture-density experiment that included six different initial spacings. After 12 growing seasons, both cultural intensity (operational versus intensive) and planting density significantly affected total above-ground biomass accumulation, but their interaction was not significant. Stands managed under the intensive culture regime accumulated more total biomass than the operational treatment. Stands planted at a 3.66 × 3.66 m (747 trees ha^{-1}) spacing had significantly less total biomass than all other spacings, but no significant differences in total biomass were found among the remaining spacings, which ranged from 2.44 × 2.74 m (1496 trees ha^{-1}) to 1.83 × 1.22 m (4479 trees ha^{-1}). These results suggest that planting seedlings on a 2.4 × 2.4 m (1736 trees ha^{-1}) to 3.0 × 3.0 m (or equivalent spacing; 1111 trees ha^{-1}) spacing will generally provide flexibility for meeting most landowner objectives with loblolly pine (Smith and Strub, 1991).

Munsell and Fox (2010) conducted a feasibility analysis for increasing woody biomass production from pine plantations in the southern USA. They examined the yields and merchandized product values associated with a 24-year rotation that included two silvicultural treatments (moderate and intensive), two planting densities (1235 trees ha^{-1} versus 1853 trees ha^{-1}), and thinning compared to a dedicated biomass crop managed on three 8-year rotations. Their results suggested that pine plantations managed intensively for a mixture of forest products, or high-density plantings managed for a dedicated biomass supply, could be profitable at current prices in the southern USA. However, biomass stumpage prices and markets would likely need to increase substantially before pine plantations would be managed solely for biomass production on cutover sites.

Alternative spacing arrangements, that also include planting seedlings of varying genetic improvement, have been proposed as a means to provide landowners with an opportunity to meet multiple timber product objectives, including biomass and saw-timber. Referred to as 'FlexStand™ systems' (ArborGen, Inc.), they may include closely spaced, dual rows of genetically improved, open-pollinated seedlings (for biomass) planted between rows of control pollinated or clonal seedlings (for saw-timber). As the stand grows and develops, the alternate biomass rows would be removed first, leaving the more valuable, controlled pollinated/clonal planting stock to meet future saw-timber objectives.

20.4.4 Thinning and fertilization

Density management through intermediate cuttings (thinning) may or may not be a component of a biofuels silvicultural system used with loblolly pine. For example, across the region, loblolly pine begins to exhibit self-thinning mortality at a basal area of about 30 m^2 ha^{-1} when established at traditional spacings (e.g. 1.8 × 3.6 m or 1543 trees ha^{-1}) used for meeting integrated forest product objectives (Jokela *et al*., 2004; Fig. 20.3). Thus, unthinned stands could either be harvested or thinned prior to reaching that level of stand density. Maximum fibre production typically occurs at the culmination of mean annual increment (MAI), which in unthinned, intensively managed loblolly pine stands may be as early as age 13 years (Martin and Jokela, 2004). It follows that the culmination of MAI in unthinned stands planted at closer initial

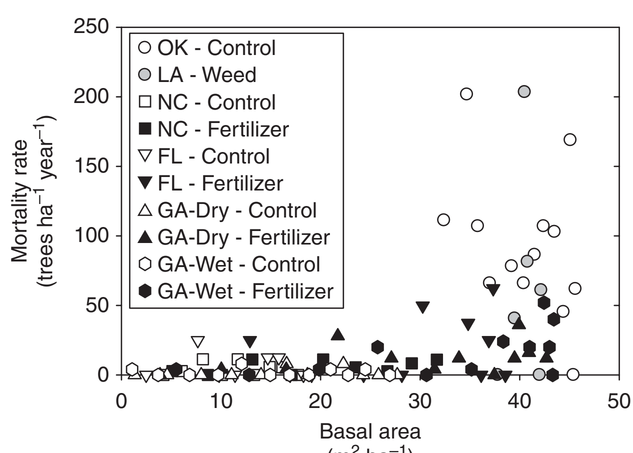


Fig. 20.3. Mortality rate of unthinned loblolly pine stands in relation to stand basal area (adapted from Jokela *et al*., 2004).

spacings could occur even earlier (e.g. 8 years; Munsell and Fox, 2010). Density management diagrams have been developed for loblolly pine to aid thinning decisions related to timing and the desired upper and lower limits of residual stocking (Dean and Baldwin, 1993, 1996). Depending upon the site, initial planting density and local market conditions, landowners managing loblolly pine stands for an integrated products objective may use their first thinning entry (between ages 10 and 15 years) to supply fibre to a biofuels market.

Soils supporting loblolly pine stands in the southern USA tend to be infertile and nutrient additions are typically required to achieve optimum rates of production (Pritchett and Comerford, 1982; Jokela *et al*., 1991a; Albaugh *et al*., 2007; Fox *et al*., 2007). Early site occupancy and the development of a large and functioning leaf area (leaf area index (LAI)) represents an important strategy for enhancing pine productivity, and correcting nutrient deficiencies through fertilizer additions is an important silvicultural tool for achieving that objective (Colbert *et al*., 1990). Phosphorus plus N, and P alone, are the nutrient elements that tend to be the most widely limiting and applied to loblolly pine stands. Applications of N alone are not generally recommended in young stands because it often stimulates competing vegetation. In some cases, K and other nutrients may limit loblolly pine growth after N and P demands have been met (Jokela, 2004; Kyle *et al*., 2005). For example, micronutrient deficiencies have been documented (Mn, Cu) in southern pine stands that were managed intensively using N + P fertilization and understorey competition control treatments (Jokela *et al*., 1991b; Vogel and Jokela, 2011).

With loblolly pine, fertilization treatments typically occur at or near time of planting and at mid-rotation. On poorly drained, P-deficient clayey soils (e.g. CRIFF A group soils), P applications typically occur in year 1 (40–50 kg ha^{-1} elemental P) and volume responses may average 2.8 to 3.5 m^3 ha^{-1} $year^{-1}$ for 20 years or longer (Pritchett and Comerford, 1982; Jokela *et al*., 1991a). Responses to P alone have also been documented on upland, well-drained Coastal Plain sites (CRIFF E and F group soils; Allen and Lein, 1998; Leggett and Kelting, 2006). Similarly, in young loblolly pine stands growing on lower Coastal Plain sites (CRIFF A, B, C, D group soils), applications of N + P (e.g. 40 kg ha^{-1} N and 45 kg ha^{-1} P) may be applied alone or in conjunction with herbaceous weed-control treatments within the first 5 years of establishment. Nitrogen and P fertilizer sources that are most commonly used on such sites include diammonium phosphate (DAP; 18-46-0), monoammonium phosphate (MAP; 11-52-0) and urea (45-0-0).

Mid-rotation fertilizer applications are commonly applied at the time of crown closure, when growth demands exceed soil supply for N and P, and nutrient deficiencies restrict loblolly pine leaf area development and stand growth (Allen *et al*., 1990; Fox *et al*., 2007). A combination of N and P is most commonly applied over either element alone because it provides the greatest probability and magnitude of growth response (Fox *et al*., 2007; Fig. 20.4).

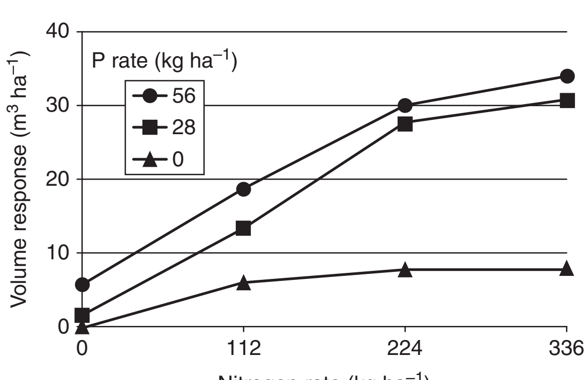


Fig. 20.4. Eight-year volume responses of loblolly pine to N and P fertilization (age 9–16 years) in the southern USA (adapted from Fox *et al*., 2007).

Application rates range from 150 to 200 kg N ha^{-1} plus 25 kg P ha^{-1} (Jokela, 2004) using DAP and urea as fertilizer sources. Growth responses may last from 6 to 10 years and average about 1.5 m^3 ha^{-1} $year^{-1}$ (Fox *et al*., 2007).

A number of diagnostic tools have been used, with varying degrees of success, for identifying loblolly pine stands that will be responsive to fertilizer additions, including soil groups, foliar analyses, soil analyses and LAI assessments. For example, critical concentrations of foliar N and P in loblolly pine stands are 1.2% and 0.11%, respectively (Allen, 1987; Jokela *et al*., 1991a). Stands that have foliar nutrient concentrations that fall below these levels would have a greater likelihood of responding to fertilizer additions, although quantitative relationships that predict the magnitudes of response are still limited. Guidelines for identifying P deficiencies based on soil analyses have been developed and responsive soils would be characterized by having Mehlich-3 extractable P levels below 6 ppm. Similarly, as LAI in loblolly pine stands is highly correlated with potential productivity (Vose and Allen, 1988; Colbert *et al*., 1990; Albaugh *et al*., 1998), mid-rotation stands may be identified as responsive to N and P fertilizer additions if projected LAI levels in fully stocked stands are less than 3.5 (Fox *et al*., 2007).

20.4.5 Treatment interactions

Understanding the importance and magnitude of interactions among silvicultural treatments may enhance the growth potential of loblolly pine stands being managed for biofuels objectives. For example, Jokela *et al*. (2000) reported on ten regional loblolly pine experiments that were established using a common study design that were treated at time of planting (i.e. control, fertilizer only (223 kg ha^{-1} DAP), herbaceous weed control only (hexazionone and sulfometuron methyl) and fertilizer + herbaceous weed control). The percentage of loblolly pine sites exhibiting significant volume responses at age 5 years were 60% for fertilizer only, 40% for herbaceous weed control only and 100% for the fertilizer + herbaceous weed control treatment. In the majority of tests, the fertilizer and herbaceous weed control treatments were additive in nature, suggesting that each treatment was independent relative to its effects on volume growth. However, when both treatments equally contribute to increased soil nutrient supply, less than additive responses may be expected (Jokela *et al*., 2000; Albaugh *et al*., 2003). After 8 years, the volume responses for the fertilizer + herbaceous weed control treatment over the untreated control averaged 100% on CRIFF A group soils (100 m^3 ha^{-1} versus 50 m^3 ha^{-1}) and 52% on CRIFF C and D group soils (48 m^3 ha^{-1} versus 32 m^3 ha^{-1}). The early treatment responses declined between ages 5 and 8 years, especially for the herbaceous weed control treatment, suggesting that additional silvicultural inputs, in the form of mid-rotation fertilizer applications, would be necessary to sustain the early growth benefits.

Genotype-by-environment interactions are less common in loblolly pine stands, especially with open-pollinated families that originated from first- or second-generation seed orchards (McKeand *et al*., 2006b). That is, families have generally exhibited stable performance (few rank changes) across sites within a climatic zone. Less information is available, however, regarding genotype-by-silviculture treatment interactions (McKeand *et al*., 1997, 2000), but these interactions could become more important as less genetically diverse full-sib families and clones are deployed using more intensive silvicultural regimes (McKeand *et al*., 2006b). For example, Roth *et al*. (2007) used full-sib family block plot experiments that included two levels of planting density and silvicultural treatment intensity, and reported significant genotype-by-location and genotype-by-silvicultural treatment intensity interactions for loblolly pine at age 5 years. The nature of the interactions and instability of family performance (volume accumulation) were mainly the result of scale effects, where certain families either outperformed or underperformed their peers with increasing intensity of silvicultural treatments.

20.4.6 Yields and rotation ages

Loblolly pine grows faster than slash pine when given adequate nutrients, producing larger diameter stems at younger ages. For example, at the end of 15 years, loblolly and slash pine on average accumulate 136 and 118 t carbon ha^{-1}, respectively (Gonzalez-Benecke *et al.*, 2010, 2011), with about 70% of the carbon in the stem, branches and needles, and over 85% of this above-ground carbon in the stem and branch wood (Johnsen *et al.*, 2004; Gonzales-Benecke *et al.*, 2011).

The expected yields of loblolly pine stands being managed for a biofuels objective will depend upon a number of factors, including site quality, silvicultural management intensity, genetics, planting density and rotation ages. Numerous growth and yield models have been developed for loblolly pine (e.g. PTAEDA4.0; FASTLOB) and most are based on traditional forest product objectives (Clutter, 1963; Sullivan and Clutter, 1972; Burkhart *et al.*, 1985; Baldwin and Feduccia, 1987; Matney and Farrar, 1992; Baldwin *et al.*, 2001; Burkhart, 2008). In addition, many studies have documented biomass accumulation (dry weight) of loblolly pine stands under varying scenarios of management intensity (Colbert *et al.*, 1990; Albaugh *et al.*, 1998; Jokela and Martin, 2000; Adegbidi *et al.*, 2002; Samuelson *et al.*, 2004; Aspinwall *et al.*, 2011). Zhao *et al.* (2012) reported in 12-year-old loblolly pine stands that total above-ground biomass accumulation averaged about 150 dry t ha^{-1} under intensive management compared to 120 dry t ha^{-1} under operational management (Samuelson *et al.*, 2008). Munsell and Fox (2010) modelled biomass yields for loblolly pine stands planted under varying management regimes (biomass, traditional, integrated, traditional + thinning and integrated + thinning), planting densities and site index. Short rotation (8 year) cumulative biomass estimates over a 24-year period for stands planted at 1235 stems ha^{-1} ranged from 215 to 336 wet t ha^{-1} for site index 19.8 m to 25.9 m, respectively. When planting density was increased to 1835 stem ha^{-1} for the same levels of site index, wet cumulative biomass yields ranged from 240 to 493 t ha^{-1}.

Other management options being considered when using loblolly pine to meet a biofuels objective involve an agroforestry intercropping system, where switchgrass (*Panicum virgatum*) is interplanted with loblolly pine. The concept recognizes that the forest has the potential to produce a biofuels feedstock (switchgrass) while still maintaining a supply of traditional forest products. The loblolly pine stands would be established using a relatively low planting density (740 trees ha^{-1}; 6 m between planting rows and 2.25 m within), with switchgrass interplanted between the pine rows. Once the perennial switchgrass stand has been established using herbicides, disk harrowing and seeding procedures, it could be harvested annually. The pines would be harvested occasionally when they reach merchantable sizes for meeting traditional forest products objectives. At present, however, few published studies have quantified the expected combined yields of switchgrass and loblolly pine for biofuels production (Blazier, 2009).

20.5 Tree Harvesting and Chip Processing for Bioenergy

Well-developed harvesting technologies exist to recover forest products from loblolly pine plantations. Harvesting systems have evolved from manual chainsaw and shortwood pulpwood to current highly mechanized operations in response to changing technology, costs and product specifications. Product markets encourage silvicultural and harvesting operations that minimize total cost per tonne. Landowners are incentivized to grow a stand that will maximize their economic return. The management decisions affect stocking, tree size and spacing, and rotation age. At the same time product markets define merchantability specifications including piece size, wood or fibre quality, market pricing and delivery form. The harvesting operation fits between these two with the cost and equipment requirements determined by multiple factors. The interplay of these constraints has defined the most common economically viable plantation management model with a single mid-rotation thinning treatment recovering primarily pulpwood products and a final harvest with saw-timber, oriented strand board or other higher-valued products. In most cases energy-wood is simply another potential product and is harvested using conventional operational technology. A few specialized pine energy harvesting systems have been developed and are described below.

20.5.1 Harvesting systems

Pine harvesting systems (Fig. 20.5) can be classified into two basic types, single product and multi-product. Whether in a thinning or final harvest, the simplest harvesting system takes everything to a common delivery point (single product). Nearly all pine felling is accomplished by feller-bunchers using high-speed disk sawheads (Baker and Greene, 2008). Bunches of felled trees are skidded from the stand to a roadside landing by grapple skidders. At the landing a knuckleboom log loader de-limbs and tops the trees to meet product specifications using a stationary de-limber. Finally, the loader places tree-length material on log trailers for transport to the mill.

A single product harvest operation may be used when there are very few product classes in the management treatment. For example, an early thinning with smaller diameter trees may have few product options other than energy-wood or pulpwood. Similarly, a final regeneration cut on a short rotation pine plantation may have uniform small diameter trees that are only energy-wood material. Taking everything to one market delivery point simplifies operations and maximizes the productivity of in-woods activities. As an example there are pellet mills in the southern USA that purchase tree-length pine for feedstock. This gives the pellet mill control of the debarking and chipping process to ensure product quality. The bark is used in the mill for process heat while the stemwood ends up in the pellets.

While less common, in-woods chipping may also be employed in a single-product system. Smaller diameter and shorter trees (early thinning or energy-wood) are harder to load effectively as tree-length material and may be better utilized by roadside chipping. In this system everything is skidded to the roadside. If the product specification requires low bark

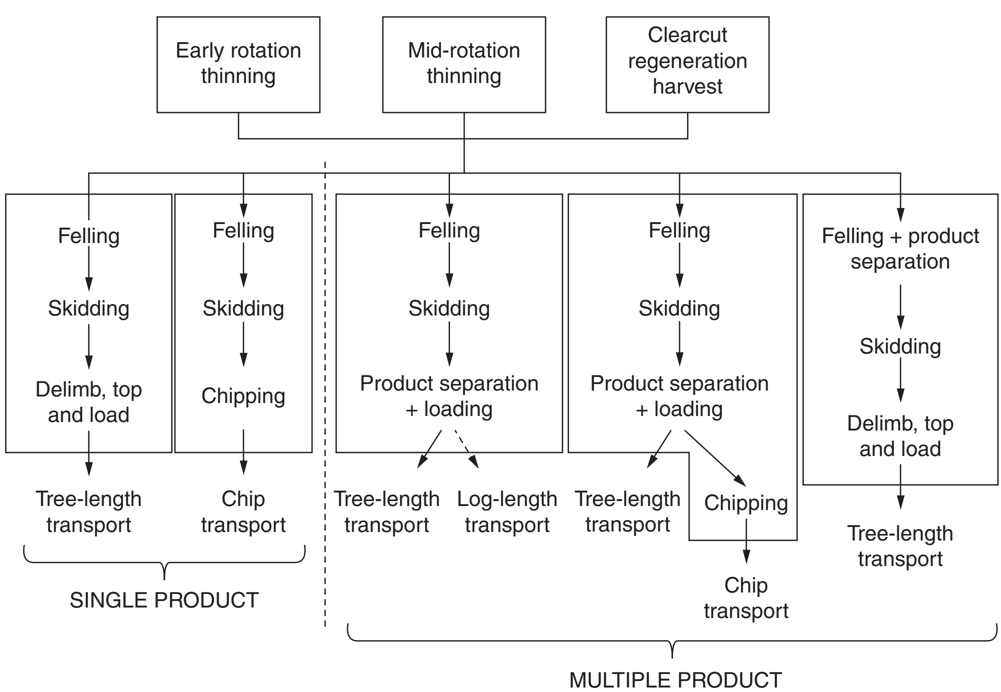


Fig. 20.5. Alternative harvesting systems for plantation pine and energy-wood.

content, the stems are passed through a flail debarker before chipping (clean chips). If product specifications are not constrained by bark content, it is faster and cheaper to process the whole tree through the chipper (whole-tree chips).

Multi-product harvesting systems are used when there is more than one product class in the stand. The system becomes more complex by introducing a sorting and product separation function at the roadside. Merchandizing may be as simple as sorting trees by product classes and loading separate trailers. More complex merchandizing involves bucking trees to meet different market specifications using a slasher saw or processor. Cass *et al* (2009) examined economic trade-offs in product sorting and found that the value differential among product classes was critical to determine the optimum number of product sorts for a given harvest situation. Product sorting adds extra handling, adding cost that must be more than offset by an increase in total value. In a region-wide study of logging contractors deHoop *et al*. (2002) found that more than half of logging contractors used between four and seven product sorts.

One version of the multi-product operation includes sorting and chipping in addition to conventional tree-length or log-length products. Westbrook *et al*. (2007) evaluated the effect of adding a small chipper to concurrently recover residues as fuel chips on a conventional southern pine harvesting operation. They found that residue utilization recovered an additional 15% volume per hectare and reduced site preparation costs by 30%. Another key finding was that the stand product mix had to include a sufficient volume of chippable material to make it worth the additional expense of bringing in another machine.

Another version of a multi-product harvesting system detailed in Fig. 20.5 is product separation at the felling stage. This may occur in a single-pass operation with the feller-buncher cutting and stacking trees in different bunches by product class. A plantation with significant hardwood ingrowth might be an example where this method would be appropriate to separate pine pulpwood from mixed whole-tree energy-wood. This system can also be implemented as a two-pass system with felling and skidding of the energy-wood prior to felling and skidding larger material. Watson *et al*. (1986) compared one- and two-pass systems and identified advantages and disadvantages of each.

While harvesting systems for thinning or final cuts utilize the same functional technology, there are some significant differences. Thinning systems require operation in a residual stand with due consideration for impacts that could affect mortality or wood quality. Stem scars on residual trees can lead to log degrade or pathogen entry. Rutting, soil disturbance and compaction can affect root systems and lead to growth and vigour impacts. Best practices to minimize impacts in thinning include selection of smaller or more manoeuvrable equipment, careful operation to reduce residual stem damage, and more attention to soil conditions and weather to avoid rutting. Equipment manoeuvrability is particularly important if the thinning pattern is a combination of row and selection harvest.

Thinning is also more expensive than final clear-cutting. On a cost per tonne basis felling usually represents the greatest single functional cost, followed by skidding and then loading. If chipping is included in woods operations it is the largest cost component. The single most important factor affecting felling productivity and cost is piece size (Visser and Stampfer, 2003). Cutting time for modern high-speed feller-bunchers is relatively unaffected by diameter over a reasonable range of tree sizes (constant time per tree). However, because piece volume is not linearly related to diameter, the volume cost curve for felling is strongly non-linear (Fig. 20.6). In the example a 10 cm diameter tree is half the diameter of a 20 cm tree but the cost per volume harvested is three times greater. The exponentially increasing costs of smaller trees establish a minimum economically viable thinning size.

20.5.2 Pine energy-wood options

Energy-wood markets introduce some new challenges and opportunities for pine harvesting. Obviously there is the potential to utilize more of the total stand volume if energy specifications accept material not otherwise

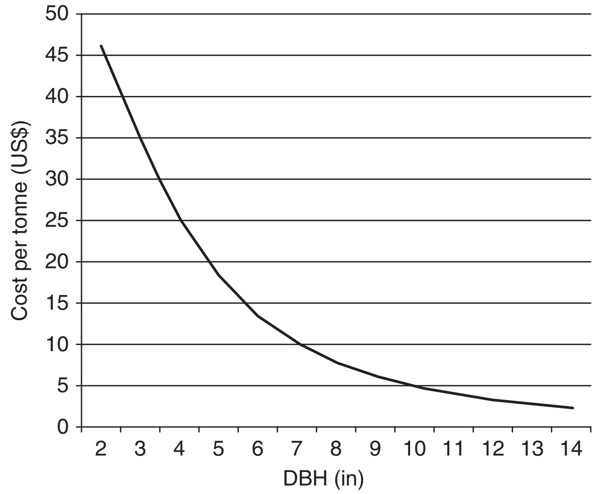


Fig. 20.6. Example felling cost function illustrating the effect of piece size on cost per tonne. DBH, diameter at breast height.

merchantable. Small diameter material, cull logs and defects and understorey hardwood encroachment are all potential energy feedstocks that can be recovered from pine stands. Logging residues like these are often cited as available bioenergy feedstock because they are considered 'waste'. Logging utilization studies (e.g. Bentley and Johnson, 2008) typically find that at least 10% of total softwood volume is left behind in conventional harvests. At an annual softwood harvest of about 170 million m^3, southern pine harvesting has a potential residue volume of about 14.5 Mt green.

Not all logging residues are technically recoverable. Current systems can recover residues from roadside processing by adding a portable grinder. These materials are often high in bark, foliage and ash and may only be suitable for direct combustion. Meadows *et al.* (2011) tested an innovative residue bundler as an alternative to chipping or grinding. They found that this system cost an additional US$13 per tonne to collect residues in bundle form. The bundles still need to be transported and ground for final utilization. Other equipment has been proposed for residue collection, including terrain chippers.

Pine understorey is another potentially available energy feedstock. This may include natural pine regeneration and hardwood ingrowth. Several versions of swath baling machines have been developed that can mow and bale understorey material up to about 15 cm in diameter. For example, do Canto *et al.* (2011) evaluated the performance of a swath baling machine in a pine stand in southern Georgia. The system showed the potential to treat about 0.5 ha h^{-1} but was only able to recover about 10 green t ha^{-1}. The economic viability of such a system is highly dependent on the volume of understorey material to be removed. Koch (1980) envisioned purpose-grown pine energy-wood with strips of dense, seeded loblolly alternating with rows of planted trees. His system proposed using a swath cutting system to harvest the seeded pine energy-wood strips at age 4 years. This concept may be viable with the new swath baling machines.

As discussed above, loblolly pine can also be grown as a single product stand for energy-wood (Munsell and Fox, 2010; Zhao *et al.*, 2012), where proposed stands would have more than 1700 trees ha^{-1} and would be harvested in a single clearcut at 8 to 14 years of age, eliminating thinning and product sorting thereby simplifying harvesting operations. Klepac *et al.* (2011) describe an ongoing test of a harvesting system optimized for high-density pine plantations. The biomass feller-buncher uses a high-speed shear to reduce costs. The new grapple skidder design increases grapple size to obtain optimal payloads. Initial results show that the specialized harvesting system will be able to collect bioenergy feedstock more efficiently than current conventional pine harvesting systems.

20.5.3 Technology to manage feedstock specifications

Energy-wood offers the potential to utilize a wider range of tree sizes. However, the conversion process can impose demanding constraints that do not apply to conventional forest products. Net heat value for example may be important if the feedstock is going directly to a thermal combustion process. While most wood has a similar higher heating value (btu per dry kg) the inherent moisture content in the wood reduces the actual heat value. Field moisture content is often about 50% (wet basis). The net heat content, if this material is delivered to a combustion process, is less than half of the potential heat value of the material because of the moisture. Thus, one specification may be moisture content. Harvesting operations that can deliver drier material would be producing feedstock with a higher market value. Currently the only demonstrated method to reduce moisture content is field drying – leaving felled material on the ground for some period of time prior to chipping or loading and transport. Cutshall *et al*. (2011) tested drying periods up to 8 weeks. They found that the moisture content of chips was reduced from 53% to 39% between chipping green and chipping dried material. This represents a 40% btu increase in the delivered final product.

Mitchell (2006) describes other bioenergy product specifications that may be important depending on conversion process. Particle size affects process variables in many types of conversion. Smaller pieces digest faster, burn faster, or densify more easily. Typical pulp chip specifications are optimized for pulp digesters but may not be optimal for bioenergy use. Thus new in-woods equipment has been developed to create 'micro-chips' that are more appropriate for bioenergy use. Micro-chips are about half the size of conventional pulp chips.

Another critical bioenergy specification may be a limit on ash content. Some uses may even specify the mineralogical composition of the ash such as percentage silica. Manipulating ash usually requires separation of bark and foliage from stemwood using a mechanical debarker. Stemwood has the lowest ash content of these three components and the most stringent ash specification would require total debarking. Less exacting specifications may be met by simply de-limbing to separate the limbs and foliage. Logging residues are inherently high in ash content and they are difficult to process. Currently, the only viable technology for cleaning logging residues is post-processing chipped material (Dooley, 2012). Chip beneficiation is one such process in which materials are separated sequentially using screening, flotation and other methods.

20.6 Bioenergy Opportunities and Challenges

Bioenergy in its most basic definition is the release of energy derived from a biological feedstock. In the case of pine as a feedstock, the available woody biomass can be defined in several ways depending on the location within the pine tree. The main stem of the pine tree has several features that make it ideal as a bioenergy feedstock. The near cylindrical shape of the main stem in conjunction with the large percentage of overall biomass tree volume make this portion of the tree the most economical to harvest and transport (Harrill and Han, 2012). The chemical composition of stemwood is of particular interest as this typically accounts for over 60% of the weight of the harvested biomass. In loblolly pine, wood chemical composition varies with cambial meristem age: juvenile wood has slightly higher lignin and lower cellulose contents than mature wood (Sykes *et al*., 2006; Yeh *et al*., 2006). Differences in lignin content with tree height are relatively small (Yeh *et al*., 2006). The greatest difference in wood chemical composition is between mature stems and severe compression wood, which forms on the underside of branches (knots) and bent stems. Severe compression wood contains ~33% more lignin and ~17% less cellulose than mature stemwood (Table 20.2).

Table 20.2. Average percentage chemical composition of loblolly and slash pine tissue.

	Juvenile wood	Mature wood	Compression wood	Bark
Cellulose	44	46	38	20
Hemicellulose	24	24	23	10
Lignin	29	27	36	50
Hydrocarbon extractives	3	3	3	12

Economics play a defining role in the final end-product of the stem material. Typically, large-diameter pine stems are converted to structural materials such as lumber, leaving the smaller-diameter stems for uses such as composites and bioenergy feedstock.

Besides transportation benefits, another advantage of the main stem is the ease with which it can be debarked. This usually results in better mill flexibility and efficiency. The bark, being high in ash content but also possessing higher heats of combustion (Howard, 1973), is ideally suited as a combustion feedstock. The resultant debarked pine stemwood is comprised of approximately 50% carbon as well as the lowest ash portion of the tree, typically between 0.1 and 0.5% (Panshin and de Zeeuw, 1980), thus making it a desirable feedstock for thermochemical processes.

One of the primary sources of available woody pine biomass is residuals, which generally encompass logging residues and pre-commercial thinnings with recent estimates of available forest harvest residuals around 54 Mt dry annually (White, 2010). Characterization of this feedstock is difficult due to the inconsistent proportion of bark, needles and clear wood percentages that individually determine the physical, chemical and thermal properties of the feedstock. Baker *et al*. (2012) examined chip properties from conventional southern pine harvests and found that ash content was generally less than 1% by weight, whereas logging residues have been found to have higher ash content because they may be contaminated with additional ash from soil contact. Although ash percentage from forest residues is markedly different from the corresponding clear-wood values, other important property differences are bulk density, mineral composition and heating value (Das *et al*., 2011).

20.6.1 Thermochemical conversion

Thermochemical conversion processes are used to breakdown lignocellulosic biomass, releasing heat that can be captured to generate power and smaller carbon-containing molecules that can be polymerized into liquid fuels. A myriad of methods is available and well known (Fig. 20.7), but only three are of practical significance for the southern pines: combustion, gasification and pyrolysis. In the following we discuss these three methods and follow this up with a discussion on biochemical approaches to releasing and capturing energy from lignocellulosic biomass.

Combustion

The combustion of lignocellulosic biomass (wood and woody residues) is the single largest form of energy production in the world, accounting for up to 97% of the world's non-industrial energy production. In essence, combustion of woody biomass is the exothermic oxidation in the presence of air of the principal wood constituents, with carbon being oxidized to carbon dioxide and hydrogen oxidized to water. This series of chemical reaction results can be useful in the production of two types of energy outputs: heat and fuelling steam turbines and steam engines both towards electricity generation. The heat produced from combustion is directly related to the bulk density of the material in conjunction with the

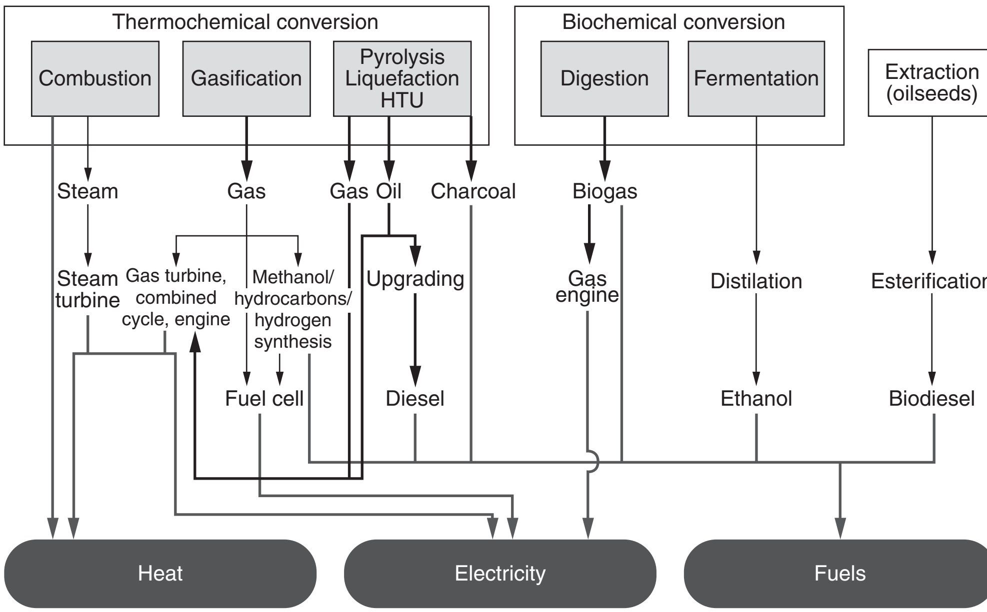


Fig. 20.7. Various thermochemical and biochemical conversion technologies for woody biomass and their various end-product scenarios (from Faaji, 2006).

energy content of the woody biomass. The energy content of woody biomass on a dry, ash-free basis falls within the range of 17 to 21 MJ kg^{-1} (McKendry, 2002a). The energy content of southern pine wood, bark and residuals falls within the upper end of the range at 19 to 21 MJ kg^{-1} (Phanphanich and Mani, 2009).

Southern pine fuel characteristics that govern the efficacy of the woody biomass feedstock are bulk density (which in turn is affected by growth features such as variants, species, geographic distribution, silviculture and age at harvest), material properties such as moisture content and ash content, particle size, and processing variables such as whole-tree chipping and debarking. Geographic distribution can also be a critical factor in overall ring density in the southern pines. For example, loblolly pine ring density is higher in the Gulf and South Atlantic regions than in the Piedmont and Hilly regions (Clark and Daniels, 2004; Jordan *et al*., 2008).

Gasification

Gasification is a three-step process resulting in the partial oxidation of biomass at temperatures in a restricted oxygen environment into a gaseous fuel. The woody biomass undergoes pyrolysis, combustion and reduction reactions resulting in a mixture of hydrogen, carbon dioxide, carbon monoxide, low molecular weight hydrocarbons (primarily methane) and nitrogen. The resulting gas mixture is commonly referred to as synthesis gas or syngas. The production of syngas generally occurs between 800 and 1200°C. Gasifier designs are typically a function of size. Smaller throughput gasifiers generally are fixed bed reactors that limit the mobility of the raw material. Gas flow within these systems is commonly referred to as updraught or downdraught due to the nature of syngas directional movement. Larger gasification systems require a greater flexibility associated with fuel types and are most typically circulating fluidized bed reactors, allowing for a more dynamic movement of particles during gasification.

The composition and scrubbing of the syngas dictates its final end use. For example, in its gaseous state syngas can be used to power gas turbines or as fuel for diesel or modified internal combustion engines. Syngas produced from woodchips via a fixed bed gasifier was used to power automobile engines in Sweden as far back as the 1920s (McKendry, 2002b). Engines run from syngas typically are used to turn generators that provide electrical power to remote locations or to supplement existing power grids. Although also showing potential for use in fuel cells, technologies are developing that convert the gaseous syngas into various chemical compounds as well as liquid transportation fuels. The Fischer-Tropsch conversion pathway was patented in 1930 (Fischer and Tropsch, 1930) but has always been limited in its use because of economic barriers. Development of catalysts with increased surface area and activation, along with techniques such as the Mobil process (Gujar *et al.*, 2009), has sparked an increase in research efforts.

Due to the heterogeneity of woody biomass as well as the complexity of a typical gasification system, evaluating the effect of woody biomass on syngas composition can be problematic. The carbon conversion reactions during biomass gasification can shift appreciably as a result of different operating conditions and thus determine syngas composition (Deglise and Magne, 1987; Devi *et al.*, 2003). Operating parameters that affect syngas composition are temperature profile within the gasification chamber (Pletka *et al.*, 2001), residence time (Babu and Chaurasia, 2003) and air supply (Chen *et al.*, 2003).

Determination of the effect various woody feedstocks have on syngas composition can be difficult because the differences can be masked by slight fluctuations in operating parameters. Geyer and Walawender (2000) showed that various *Populus* clone feedstocks had no effect on syngas composition. Evaluating at a wider range of hardwood feedstocks, Walawender and Geyer (1988) showed a greater separation of syngas composition although the differences were still small. Elder and Groom (2011) evaluated mixed hardwoods and southern pine mix in a downdraught gasifier and did see appreciable differences in the syngas composition. They evaluated the feedstocks at several flow rates and found that for all flow rates, the hardwood mix produced less carbon monoxide and more hydrogen than the southern pine mix. The carbon monoxide to hydrogen ratio is a critical factor in the conversion to a liquid transportation fuel.

It should be pointed out that although the tree species may have an effect on syngas composition, moisture content of the woody biomass has a greater effect on syngas composition. Higher moisture contents reduce thermal efficiency and thus lower reactor temperatures. The results are lower carbon monoxide levels, increased hydrogen production, lower syngas heating values and higher tar values (Wei *et al.*, 2009).

Pyrolysis

Pyrolysis as it relates to woody biomass is broadly defined as the thermal decomposition of biomass in a non- or low-oxygen environment. Unlike gasification in which there is one desired end-product (syngas), the pyrolysis process produces a liquid tar, a hydrocarbon-rich gas mixture and a solid carbon-rich char. The proportions of these components are primarily attributable to the processing method. The production of char is favoured by low processing temperatures and long residence times. Conversely, moderate temperatures and short residence times optimize the liquid fraction, with high temperatures and long residence times favouring the production of gases (Bridgwater, 2003).

Pyrolysis processes are most often categorized as conventional or fast pyrolysis (Mohan *et al.*, 2006). Pyrolyses are varied in design and are often conducted at temperatures somewhere between the extremes of conventional and fast pyrolysis. Conventional pyrolysis is typically between 400 and 600°C with residence times from 5 to 30 min (Bridgwater, 2003). Fast pyrolysis operates in the same general temperature range (400–550°C) but relies on shorter residence times (<2 s) and increased heat transfer rates thus requiring ground feedstocks (Mohan *et al.*, 2006). Pyrolysis is continuing to evolve with the development of processes such as vacuum pyrolysis (Garcia-Perez *et al.*, 2006), flash pyrolysis (Demirbas, 2002) and vacuum flash pyrolysis (Goyal *et al.*, 2008).

No matter the method of pyrolysis, the end result is a crude liquid referred to as pyrolysis oil, bio-oil, bio-crude-oil and others. The crude pyrolysis liquid is usually dark brown and is composed of a very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water from both the original moisture and reaction product. Solid char and dissolved alkali metals from ash are often present in what is actually a micro-emulsion (Bridgwater, 2003). Although the pyrolytic liquid fraction is composed of a wide spectrum of organic substances (Bridgwater, 1994), the fraction actually consists of two phases: an aqueous phase containing a wide variety of organo-oxygen low molecular weight compounds and higher molecular weight compounds comprising the non-aqueous phase containing insoluble organics (Wenzl, 1970).

The pyrolysis oil can be burned, converted to diesel or other liquid transportation fuels, or used as a chemical feedstock for a suite of commodity products such as adhesives and fertilizers as well as more specialized chemicals such as acetic acid and levoglucosan (Bridgwater, 2003). All chemicals are attractive possibilities due to their much higher added value compared to fuels and energy products, and lead to the possibility of a biorefinery concept in which the optimum combinations of fuels and chemicals are produced.

Evaluating the link between woody biomass species and pyrolysis oil can be challenging due to heterogeneous variables such as juvenility, bark percentage and location within a tree (Table 20.2). Wood that has had the bark removed generally results in a pyrolysis oil yield of 72 to 80% on a weight basis (Mohan *et al*., 2006), depending on the relative amounts of cellulose and lignin. Pyrolysis oil yields tend to favour lower lignin contents (Mohan *et al*., 2006). Typically, the lignin content of hardwoods is in the range of 21 ± 3% as opposed to the 27 ± 2% range associated with *Pinus* spp. (Pettersen, 1984). Bark is also high in lignin compared to wood, generally yielding 60–65% pyrolysis oil (Mohan *et al*., 2006).

20.6.2 Biochemical conversion

For southern pine, thermochemical methods have been favoured over biochemical conversion technologies because of the relatively lower wood sugar levels compared with hardwood (angiosperm) tree species. However, despite lower sugar content, efficient methods for chemical and biochemical conversion of pine (softwood trees) wood to ethanol have been demonstrated, and cost modelling supports the potential of using these conversion technologies at commercial scales (Frederick *et al*., 2008; Zhu *et al*., 2010). Concentrated acid hydrolysis to isolate sugars is being commercialized, with a large production facility being built in Mississippi that will use southern pine wood.

Biochemical conversion relies on recovering the sugars present in cellulose and hemicelluloses for fermentation by microbes to produce fuel and other valuable chemicals. A major impediment to cost-effective production of sugars is the inherent recalcitrance of the plant lignocellulosic cell walls to degradation (Himmel *et al*., 2006). Biochemical conversion methods involve biomass size reduction, pretreatment, hydrolysis/saccharification, microbial fermentation and distillation. While wood can be efficiently chipped, higher amounts of energy are needed for further size reduction and pretreatment compared with lignocellulosic biomass from grasses and crop residues, largely due to the higher density and lignin content in pine wood. Two main approaches have been investigated for solubilizing sugars from lignocellulosic biomass. Concentrated acid at low temperatures directly hydrolyses the lignocellulosic biomass into simple sugars, which are separated from the lignin and acid prior to fermentation (Taherzadeh and Keikhosro, 2007). Acid hydrolysis works with minimal changes in protocol with lignocellulosic biomass, including southern pine, with near theoretical yields of sugars (Galbe and Zacchi, 2002). The other main approach is to pretreat the biomass to increase the surface area and accessibility to enzymatic degradation, thereby increasing the efficiency of saccharification and final sugar yields.

A large number of pretreatment methods have been developed and tested with grass and woody biomass (Mosier *et al*., 2006). Steam explosion has been tested extensively and is a low-cost effective pretreatment method for grass and hardwood biomass; however, with pine wood addition of dilute acid is required and results in more condensation and enrichment of lignin and yields of sugars are adversely affected (Shevchenko *et al*., 2001). With wood from pine, modified chemical pulping methods appear to be more effective pretreatment approaches. For example, the SPORL pretreatment method with a furfural removal coupled with enzymatic hydrolysis and yeast fermentation works effectively with pine wood, yielding 304 l per dry tonne (Zhu *et al*., 2010). A significant advantage of the SPORL pretreatment method is that it starts with wood chips and partial removal of lignin dramatically reduces the energy of fiberization (Zhu *et al*., 2009), thereby increasing the surface area and accessibility of the cellulose and hemicelluloses to enzymatic degradation.

20.6.3 Improving pines for bioenergy

For the bioenergy and biofuel market to expand with southern pine plantations as a dedicated source of biomass, continued developments that decrease delivered pine biomass cost, increase the conversion efficiency to bioenergy and biofuels and improve value are needed. Total energy yield depends on the efficiency of the growing and harvesting system, as well as the efficiency of converting biomass to usable energy. Energy yield per hectare per year is especially important for biofuels as the efficiency of conversion of different sources of biomass vary for each processing method and fuel synthesis approach. Thus, energy yield on a land area and time basis can be increased by improving growth and biomass yields, carbon allocation to harvested components, and partitioning of carbon into compounds that enhance the yield of energy and fuels from biomass.

Simulated returns of three 8-year biomass rotations with a 24-year mixed product rotation indicate that with intensive management and a typical planting density, a stumpage price of US$11 per wet tonne would return the same value to the landowner as the longer mixed traditional product rotation (Munsell and Fox, 2010). This suggests that increases in biomass yield of short rotation, intensively managed stands will bring additional value to the landowner and lower delivered wood costs while helping to maintain sustainable supplies, and increase in energy per hectare per year. Increasing stem volume has been a principal focus of tree improvement programmes, and genetically improved loblolly and slash pine breeding populations grow faster and yield substantially more wood than unimproved pines (Li *et al*., 1999; Vergara *et al*., 2004). As discussed earlier, continued focus on breeding and selecting for faster growth will benefit both traditional and bioenergy/biofuel markets.

20.7 Sustainability in Southern Pine Bioenergy Systems

We have demonstrated that the southern pines (especially loblolly and slash pines) are strong candidates for providing feedstocks for bioenergy products in the southern USA. The goal of sustainable use of native forests is complex and controversial (Nambiar, 1996). However, as rotations become shorter and above-ground organic matter removal becomes more complete, pine silviculture for bioenergy products becomes more akin to agriculture. Similar to increases in agricultural productivity via the Green Revolution, improved silviculture has already, in fact, increased productivity of loblolly pine plantations in the southern USA more than fourfold (Munsell and Fox, 2010). In addition, there is a reliable history of successful multi-rotation tree plantations across an array of environments worldwide (Nambiar, 1996). Where pine plantations in the southern USA use native species, intensively managed tree plantations across the rest of the world more often than not utilize exotic species. As in agriculture, one question is if short rotation intensive culture for bioenergy production is sustainable in the long term. First, of course, we need to define sustainability. One basic goal of sustainable short rotation intensive culture should be that the trend in productivity is non-declining over successive rotations (Nambiar, 1996). However, we should also endeavour to increase productivity over time by applying further advances in forest genetics and silviculture tailored to specific site needs.

There is a deep history of successful plantation forestry around the world (Nambiar, 1996). However, the concept of sustainable use of forests is still complex and controversial. In his treatise on sustainable productivity, Powers (1999) asserted that obvious declines in productivity in plantations using conventional logging are rare and can be attributed to poor management. However, clear declines have been observed following whole-tree harvesting (WTH) operations as would occur in short rotation bioenergy plantations. Sitka spruce (*Picea sitchensis*) trees following WTH were 18% shorter than controls after 9 years (Proe and Dutch, 1994). Trees from the WTH plots had substantially less N, P and K than controls. On a nitrogen-limited site following WTH, 24-year-old Scots pine (*Pinus sylvestris*) trees had 20% less wood and bark biomass than trees from the conventionally harvested treatment (Egnell and Valinger, 2003). Similarly, 31 years after treatments were imposed, basal area of Norway spruce (*Picea abies*) was 25% less than trees from the conventionally harvested plots (Egnell, 2011). This reduction was due to a temporary reduction in growth in years 8 to 12 when foliar N was also observed to be low. He suggested N fertilization would have ameliorated the response. Like the cases above, yields from radiata pine (*Pinus radiata*) plantations (not subjected to WTH) on sites low in nutrients declined over time (Keeves, 1966). However, research on *P. radiata* silviculture in Australia has resulted in subsequent plantations being highly productive (Nambiar, 1996).

In the late 1980s and early 1990s, the US Forest Service initiated a series of studies called the Long-Term Soil Productivity Studies (LTSP), which among other factors examined WTH across an array of forest types. Generally, after 10 years, WTH has had no impact on site productivity (Powers *et al.*, 2005) similar to 15-year results of Johnson and Todd (1998) in a mixed oak stand in Tennessee, and specifically, WTH did not impact 10 year productivity of loblolly pine stands in North Carolina and Louisiana (Sanchez *et al.*, 2006). In the loblolly pine examples, productivity declines were negligible even when WTH was combined with total surface organic removal.

Again, we should not only strive to sustain basic site productivity but to maintain, and even increase, high levels of production achievable via intensive forestry (Fox, 2000). Earlier in this chapter we focused on the importance of nutrient management in southern pine intensive forestry. Soil management is seen increasingly as the basis for sustainable forest productivity (Nambiar, 1996; Powers *et al.*, 2005). Loblolly pine grown in factorial combination of nutrient and water treatments on a droughty site indicated the overwhelming importance of soil nutrition in loblolly pine productivity (Albaugh *et al.*, 2004). Given the state of knowledge of nutrient supply and demand in loblolly pine, fertilization will clearly be required to sustain high productivity on most sites in the southern USA (Eisenbies *et al.*, 2009). We also discussed the importance of tree improvement for growth and pest resistance and its requirement in continuing to increase productivity in loblolly pine plantations.

It has been claimed that intensively managed monoculture plantations are at greater risk for catastrophic loss than low intensity, multi-species plantations, however evidence to this effect is minimal (Nambiar, 1996). Risks, for southern pine bioenergy plantation monocultures exist, but we consider them minor based on the vast degree of confirmation from traditional and the more intensive southern pine culture of recent decades. In fact, risks from abiotic agents such as hurricanes (Johnsen *et al.*, 2009) become lower, and matching pest-resistant genotypes to site become easier as rotation ages become shorter.

Short rotation intensive culture for bioenergy production will result in more mechanical entries into plantations potentially increasing soil bulk density and thus decreasing soil porosity (Powers *et al.*, 2005). After two decades, topsoil removal with moderate and substantial compaction reduced stand volumes by 8 and 42%, respectively (Murphy *et al.*, 2004), in radiata pine stands. However, the effects of topsoil removal and compaction were confounded and could not be isolated. In the LTSP experiments, soil compaction was included as a discrete treatment so compaction responses could be isolated; forest productivity responses depended on other factors. Production declined with compaction on compacted clays and increased on sands (Powers *et al.*, 2005). In their further work on mechanical harvesting impacts on productivity, Eisenbies *et al.* (2006, 2007) found that productivity was not reduced by soil physical disturbances. These results suggest that bedding (wet sites) and other tillage such as subsoiling or ripping (dry sites) may become more important as harvesting operations on a site become more frequent (Edwards *et al.*, 2006) such as will occur in bioenergy plantations.

Is there an indicator that can be simply measured to track sustainability and provide warnings as to obstructions to its continuity? Such indicators will likely be soil based. One such indicator suggested by Nambiar (1996) and expounded upon by Sanchez (1998) is the quantification of soil organic matter as it is so entwined with nutrient and water retention. However, loblolly pine plantations do not appear to be impacted by severe alterations of soil organic matter. In the LTSP experiments, after 10 years, soil C concentrations were reduced from the removal of all surface organic matter but there were negligible effects on growth rates. In the WTH-only plots soil organic matter was not impacted (Powers *et al*., 2005), similar to results observed across four disparate hardwood and pine forests in the southern USA (Johnson *et al*., 2002). The most likely reason is that following harvest, fine and coarse root decomposition inputs C into the soil. Data from the North Carolina loblolly pine LTSP installation shows a temporary pulse of soil C concentration over the 10-year period (Johnsen *et al*., 2004). Such soil C inputs will even be higher in loblolly pine if taproot decomposition is considered (Ludovici *et al*., 2002; Maier and Johnsen, 2010; Maier *et al*., 2012).

Forest productivity has been shown to be directly related to the fertility rating (FR) as encompassed in the model 3-PG (Physiological Principles Predicting Growth, Landsberg and Waring (1997)), which is a simple process-based, stand-level model of growth. The FR ranges from 0 to 1 and for the most part has been estimated by statistical 'fitting' from representative calibration stands and testing the calibrated model on adjacent stands (Landsberg *et al*., 2001) or stands of the same species subjected to similar management (Sands and Landsberg, 2002). Progress has been made in relating FR to soil texture (Sampson *et al*., 2008). Thus, FR might provide a basis for tracking southern pine bioenergy plantation sustainability if it can be related to a set of simply measured soil properties. Therefore, continued research in this area might prove particularly fruitful. For now, however, sustainability will need to be tracked via subsampling productivity of bioenergy operations, stratified perhaps by soil type, over time.

Thus, it is very likely that southern pine energy plantations' productivity can be sustained and even increased over time. The goal will be to direct environmental resources such as light, water and nutrients to the crop trees via the judicious use of herbicides, pesticides, fertilizer and site preparation and to do so in a manner that takes into account the impacts of increasing vegetation and nutrient removals and, perhaps, the impact of more intensive mechanical harvesting. Continued genetic improvements in growth rate, pest and pathogen resistance will enhance productivity and value. A plethora of research (Jokela *et al*., 2004; Carter and Foster 2006; Vance *et al*., 2010) can be directed toward these efforts, and the infrastructure is in place to research issues that might arise or are particular to the use of southern pine as a bioenergy crop for feedstock production.

20.8 Summary and Conclusions

The southern pines, particularly loblolly and slash pines, offer many advantages as lignocellulosic feedstocks for bioenergy and biofuel production. Silvicultural practices and genetic improvements in planting stocks have been implemented broadly on millions of hectares of land across the southern USA where food crop production is not viable. Furthermore, southern pine energy-wood plantation productivity can be sustained over time and even increased with continuing genetic and silvicultural improvements. The emerging energy-wood market product specifications offer the potential to utilize smaller trees than traditional markets (i.e. pulpwood, saw-timber) opening new opportunities for earlier harvests (i.e. thinning or short rotations), closer tree-to-tree spacing and thus better site utilization. However, the higher costs associated with handling greater numbers of small trees needs to be overcome to improve the economic feasibility of delivering southern pine biomass for transportation fuels that are inherently of limited value. Altering wood chemical composition through genetics offers the opportunity to enhance energy yields and provide higher value chemical feedstocks that will improve the economics of southern pine energy-wood production.

References

Adegbidi, H.G., Jokela, E.J., Comerford, N.B. and Barros, N.F. (2002) Biomass development of intensively managed loblolly pine plantations growing on spodosols in the southeastern USA. *Forest Ecology and Management* 167, 91–102.

Albaugh, T.J., Allen, H.L., Dougherty, P.M., Kress, L.W. and King, J.S. (1998) Leaf-area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *Forest Science* 44, 317–328.

Albaugh, T.J., Allen, H.L., Zutter, B.R. and Quicke, H.E. (2003) Vegetation control and fertilization in midrotation *Pinus taeda* stands in southeastern United States. *Annals Forest Science* 60, 619–624.

Albaugh, T.A., Allen, H.L., Dougherty, P.M. and Johnsen, K.H. (2004) Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *Forest Ecology and Management* 192, 3–19.

Albaugh, T.J., Allen, H.L. and Fox, T.R. (2007) Historical patterns of forest fertilization in the southeastern United States. *Southern Journal of Applied Forestry* 31(3), 129–137.

Allen, H.L. (1987) Fertilizers: adding nutrients for enhanced forest productivity. *Journal of Forestry* 85, 37–46.

Allen, H.L. and Lein, S. (1998) Effects of site preparation, early fertilization, and weed control on 14-year old loblolly pine. In: *Proceedings Southern Weed Science Society* 51, 104–110.

Allen, H.L., Dougherty, P.M. and Campbell, R.G. (1990) Manipulation of water and nutrients – practice and opportunity in southern US pine forests. *Forest Ecology and Management* 30, 437–453.

Aspinwall, M.J., King, J.S., McKeand, S.E. and Bullock, B.P. (2011) Genetic effects on stand-level uniformity, and above- and belowground biomass production in juvenile loblolly pine. *Forest Ecology and Management* 262, 609–619.

Atwood, R.A., White, T.L. and Huber, D.A. (2002) Genetic parameters and gains for growth and wood properties in Florida source loblolly pine in the southeastern United States. *Canadian Journal of Forest Research* 32, 1025–1038.

Babu, B.V. and Chaurasia, A.S. (2003) Modeling, simulation, and estimation of optimum parameters in pyrolysis of biomass. *Energy Conversion and Management* 44(13), 2135–2158.

Baker, S. and Greene, D. (2008) Changes in Georgia's logging workforce, 1987-2007. *Southern Journal of Applied Forestry* 32(2), 60–68.

Baker, S., Greene, D. and Wilson, A. (2012) Fuel characteristics of woods – run whole tree southern pine chips. *Biomass and Bioenergy* 37, 67–72.

Baldwin, V.C., Jr and Feduccia, D.P. (1987) Loblolly pine growth and yield prediction for managed West Gulf plantations. *Research Paper* SO-236. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, Louisiana, 27 pp.

Baldwin, V.C., Jr, Burkhart, H.E., Westfall, J.A. and Peterson, K.D. (2001) Linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. *Forest Science* 47, 77–82.

Belonger, P.J., McKeand, S.E. and Jett, J.B. (1996) Genetic and environmental effects on biomass production and wood density in loblolly pine. In: Dieters, M.J., Matheson, A.C., Nikles, D.G., Harwood, C.E. and Walker, S.M. (eds) *Tree Improvement for Sustainable Tropical Forestry*. Proc. QFRI-IUFRO Conference, Caloundra, Queensland, Australia, 27 October–1 November 1996, pp. 307–310.

Bentley, J.W. and Johnson, T.G. (2008) Alabama harvest and utilization study. Resource Bulletin SRS-141. US Department of Agriculture Forest Service, Southern Research Station, Asheville, North Carolina, 24 pp.

Blazier, M. (2009) Perfect pair for biofuel: switchgrass and trees. Louisiana Agriculture. Available at: http://text.lsuagcenter.com/en/communications/publications/agmag/Archive/2009/fall/Perfect+Pair+for+Biofuel+Switchgrass+and+Trees.htm (accessed 1 June 2012).

Bridgwater, A.V. (1994) Catalysis in thermal biomass conversion. *Applied Catalysis A: General* 116 (1–2), 5–47.

Bridgwater, A.V. (2003) Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal* 91(2–3), 87–102.

Burkhart, H.E. (2008) Modelling growth and yield for intensively managed forests. *Forest Science* 24, 173–180.

Burkhart, H.E., Cloeren, D.C. and Amateis, R.L. (1985) Yield relationships in unthinned loblolly pine plantations on cutover, site-prepared lands. *Southern Journal of Applied Forestry* 9, 84–91.

Byram, T.D., Myszewski, J.H., Gwaze, D.P. and Lowe, W.J. (2005) Improving wood quality in the western gulf forest tree improvement program: the problem of multiple breeding objectives. *Tree Genetics and Genomes* 1, 85–92.

Carter, M.C. and Foster, D.C. (2006) Milestones and millstones: a retrospective on 50 years of research to improve productivity in loblolly pine plantations. *Forest Ecology and Management* 227, 137–144.

Cass, R.D., Baker, S. and Greene, D. (2009) Costs and productivity impacts of product sorting on conventional ground-based timber harvesting operations. *Forest Products Journal* 59(11/12), 108–114.

Chen, G., Andries, J., Luo, Z. and Spliethoff, H. (2003) Biomass pyrolysis/gasification for product gas: the overall investigation of parametric effects. *Energy Conversion and Management* 44(11), 1875–1884.

Clark, A. and Daniels, R. (2004) Modeling the effect of physiogeographic region on wood properties of planted loblolly pine in the southern United States. In: *Connection between Forest Resource and Wood Quality: Modeling Approaches and Simulation Software*, Fourth Workshop IUFRO Working Party S5.01-04, 8–15 September 2002, Harrison Hot Springs, British Columbia. INRA-Centre de Recherches de Nancy, France, pp. 54–60.

Clutter, J.L. (1963) Compatible growth and yield models for loblolly pine. *Forest Science* 9, 354–371.

Colbert, S.R., Jokela, E.J. and Neary, D.G. (1990) Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *Forest Science* 36, 995–1014.

Conner, R.C. and Hartsell, A.J. (2002) Forest area and conditions. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Resource Assessment*. USDA Forest Service, General Technical Report SRS-53, Asheville, North Carolina, 635 pp.

Cutshall, J., Greene, D., Baker, S. and Mitchell, D. (2011) Transpirational drying effects on energy and ash content from wholetree chipping. In: *Proceedings of the 34th Council on Forest Engineering meeting*, Quebec City, Quebec, 9 pp.

Das, K.C., Singh, K., Bibens, B., Hilten, R., Baker, S.A., Greene, W.D. and Peterson, J.D. (2011) Pyrolysis characteristics of forest residues obtained from different harvesting methods. *Applied Engineering in Agriculture* 27(1), 107–113.

Dean, T.J. and Baldwin, V.C., Jr (1993) Using a density management diagram to develop thinning schedules for loblolly pine plantations. *Research Paper* SO-275. US Department of Agriculture, Forest Service, Southern Research Station, New Orleans, Louisiana, 7 pp.

Dean, T.J. and Baldwin, V.C. (1996) Growth in loblolly pine plantations as a function of stand density and canopy properties. *Forest Ecology and Management* 82, 49–58.

Deglise, X. and Magne, P. (1987) Pyrolysis and industrial charcoal. In: *Biomass: Regenerable Energy*. John Wiley and Sons, London, pp. 221–235.

deHoop, C.F., Egan, A.F., Greene, W.D. and Mayo, J.H. (2002) Surveys of the logging contractor population – eight southern states and Maine. *Working Paper 55*. Louisiana Forest Products Development Center, Louisiana State University, 13 pp.

Demirbas, A. (2002) Analysis of liquid products from biomass via flash pyrolysis. *Energy Sources* 24(2), 337–345.

Devi, L., Ptasinski, K.J. and Janssen, F.J.J.G. (2003) A review of the primary measures for tar elimination in biomass gasification processes. *Biomass and Bioenergy* 24, 125–140.

do Canto, J.L., Klepac, J., Rummer, B., Savoie, P. and Seixas, F. (2011) Evaluation of two round baling systems for harvesting understory biomass. *Biomass and Bioenergy* 35, 2163–2170.

Dooley, J. (2012) Beneficiation of chipped and shredded woody biomass. *Abstract at International Wood Composites Symposium*, 11–14 April 2012. Washington State University, Seattle. Pullman, Washington, USA.

Edwards, S.L., Ezell, A.W. and Demarais, S. (2006) A comparison of planted loblolly pine (*Pinus taeda*) growth in areas receiving different levels of establishment regime intensity. *Journal of Sustainable Forestry* 23, 1–16.

Egnell, G. (2011) Is the productivity decline in Norway spruce following whole-tree harvesting in the final felling in boreal Sweden permanent or temporary? *Forest Ecology and Management* 261, 148–153.

Egnell, G. and Valinger, E. (2003) Survival, growth and growth allocation of planted scots pine trees after different levels of biomass removal in clear felling. *Forest Ecology and Management* 177, 65–74.

Eisenbies, M.H., Burger, J.A., Aust, W.M., Patterson, S.C. and Fox, T.R. (2006) Assessing change in soil-site productivity on intensively managed loblolly pine plantations. *Soil Science Society of America Journal* 70, 130–140.

Eisenbies, M.H., Burger, J.A., Aust, W.M. and Patterson, S.C. (2007) Changes in site productivity and recovery of soil properties following wet- and dry-weather harvesting disturbance in the Atlantic Coastal Plain for a stand of age 10 years. *Canadian Journal of Forest Research* 37, 1336–1348.

Eisenbies, M.H., Vance, E.D., Aust, W.M. and Seiler, J.R. (2009) Intensive utilization of harvest residues in southern pine plantations: quantities available and implications for nutrient budgets and sustainable site productivity. *Bioenergy Research* 2, 90–98.

Elder, T. and Groom, L.H. (2011) Pilot-scale gasification of woody biomass. *Biomass and Bioenergy* 35, 3522–3528.

Erickson, V., Aubry, C., Berrang, P., Blush, T., Bower, A., Crane, B., DeSpain, T., Gwaze, D., Hamlin, J., Horning, M., Johnson, R., Mahalovich, M., Maldonado, M., Sniezko, R. and St Clair, B. (2012) *Genetic Resource Management and Climate Change: Genetic Options for Adapting National Forests to Climate Change*. USDA Forest Service, Forest Management, Washington, DC, 24 pp.

Evans, J.M. and Cohen, M.J. (2009) Regional water resource implications of bioethanol production in the southeastern United States. *Global Change Biology* 15, 2261–2273.

Faaji, A. (2006) Modern biomass conversion technologies. *Mitigation and Adaption Strategies for Global Change* 11, 343–375.

Fischer, F. and Tropsch, H. (1930) Process for the production of paraffin-hydrocarbons with more than one carbon atom. *US Patent Number* 1,746,464. 3 pp.

Fisher, R.F. (1981) Soils interpretations for silviculture in the southeastern Coastal Plain. In: Barnett, J. (ed.) *Proceedings of the First Biennial Southern Silvicultural Research Conference*, Atlanta, Georgia, 6–7 November 1980. USDA Forest Service General Technical Report SO-GTR-34, pp. 323–330.

Fox, T.R. (2000) Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* 138, 187–202.

Fox, T.R. (2004) Species deployment strategies for the southern pines: site specific management practices for the flatwoods of Georgia and Florida. In: Dickens, E.D., Barnett, J.P., Hubbard, W.G. and Jokela, E.J. (eds) *Slash Pine: still growing and growing! Proceedings of the Slash Pine Symposium, General Technical Report 76*, US Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina, pp. 50–55.

Fox, T.R., Allen, H.L., Albaugh, T.J., Rubilar, R. and Carlson, C.A. (2007) Tree nutrition and forest fertilization of pine plantations in the southern United States. *Southern Journal of Applied Forestry* 31, 5–11.

Frederick, W.J. Jr, Lien, S.J., Courchene, C.E., DeMartini, N.A., Ragauskas, A.J. and Iisa, K. (2008) Production of ethanol from carbohydrates from loblolly pine: a technical and economic assessment. *Bioresource Technology* 99(11), 5051–5057.

Galbe, M. and Zacchi, G. (2002) A review of the production of ethanol from softwood. *Applied Microbiology and Biotechnology* 59, 618–628.

Garcia-Perez, M., Lappas, P., Hughes, P., Dell, L., Chaala, A. Kretschmer, D. and Roy, C. (2006) Evaporation and combustion characteristics of biomass vacuum pyrolysis oils. *IFRF Combustion Journal*, Volume (2006), 200601, 28 pp.

Gent, J.A., Allen, H.L., Campbell, R.G. and Wells, C.G. (1986) Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. *Southern Journal of Applied Forestry* 10, 124–128.

Geyer, W.A. and Walawender, W.P. (2000) Biomass and gasification properties of young *Populus* clones. *Wood and Fiber Science* 32(3), 375–384.

Gonzalez-Benecke, C.A., Martin, T.A., Cropper, W.P. Jr and Bracho, R. (2010) Forest management effects on *in situ* and *ex situ* slash pine forest carbon balance. *Forest Ecology and Management* 260, 795–805.

Gonzalez-Benecke, C.A., Martin, T.A., Jokela, E.J. and De La Torre, R. (2011) A flexible hybrid model of life cycle carbon balance for loblolly pine (*Pinus taeda* L.) management systems. *Forests* 2, 749–776.

Goyal, H.B., Seal, D. and Saxena, R.C. (2008) Bio-fuels from thermochemical conversion of renewable resources: a review. *Renewable and Sustainable Energy Reviews* 12(2), 504–517.

Gräns, O.A.D. (2012) Effects of genetics and silviculture and their interactions on loblolly pine and Norway spruce growth and wood properties. PhD dissertation, NC State University, Raleigh, North Carolina, 181 pp. (Available at: http://repository.lib.ncsu.edu/ir/bitstream/1840.16/7616/1/etd.pdf)

Gujar, A.C., Guda, V.K., Nolan, M., Yan, Q., Toghiani, H. and White, M.G. (2009) Reactions of methanol and higher alcohols over H-ZSM-5. *Applied Catalysis A: General* 363(1–2), 115–121.

Harrill, H. and Han, H.-S. (2012) Productivity and cost of integrated harvesting of wood chips and sawlogs in stand conversion. *International Journal Forestry Research*, Volume (2012), 893079, 10 pp.

Harrington, T.B. and Howell, K.D. (1998) Planting cost, survival, and growth one to three years after establishing loblolly pine seedlings with straight, deformed, or pruned taproots. *New Forests* 15, 193–204.

Harvey, B.G., Wright, M.E. and Quintana, R.L. (2010) High-density renewable fuels based on selective dimerization of pinenes. *Energy Fuels* 24, 267–273.

Himmel, M.E., Ding, S.-Y., Johnson, D.K., Adney, W.S., Nimlos, M.R., Brady, J.W. and Foust, T.D. (2006) Biomass recalcitrance: engineering plants and enzymes for biofuels production. *Science* 315, 804–807.

Howard, E.T. (1973) Heat of combustion of various southern pine materials. *Wood Science* 5(3), 194–197.

Johnsen, K.H., Teskey, R., Samuelson, L., Butnor, J., Maier, C., Sampson, D. and McKeand, S. (2004) Carbon sequestration in loblolly pine plantations: methods, limitations and research needs for estimating storage pools. In: Rausche, M.H.M. and Johnsen K.H. (eds) *Southern Forest Science: Past, Present, and Future*. General Technical Report SRS-75, USDA Forest Service, Southern Research Station, Asheville, North Carolina, 394 pp.

Johnsen, K.H., Butnor, J.R., Kush, J.S., Schmidtling, R.C. and Nelson, C.D. (2009) Longleaf pine displays less wind damage than loblolly pine. *Southern Journal of Applied Forestry* 33, 178–181.

Johnson, D.W. and Todd, D.E. (1998) Harvesting effects on long-term changes in nutrient pools of mixed oak forest. *Soil Science Society of America Journal* 62, 1725–1735.

Johnson, D.W., Knoepp, J.D., Swank, W.T., Shan, J., Morris, L.A., Van Lear, D.H. and Kapeluck, P.P. (2002) Effects of forest management on soil carbon: results from some long-term resampling studies. *Environmental Pollutio*n 116, S201–S208.

Jokela, E.J. (2004) Nutrient management of southern pines. In: Dickens, E.D., Barnett, J.P., Hubbard, W.G. and Jokela, E.J. (eds) Slash Pine: still growing and growing! *Proceeding of the Slash Pine Symposium, USDA Forest Service General Technical Report* SRS-76, pp. 27–35.

Jokela, E.J. and Martin, T.A. (2000) Effects of ontogeny and soil nutrient supply on production, allocation and leaf area efficiency in loblolly and slash pine stands. *Canadian Journal Forest Research* 30, 1511–1524.

Jokela, E.J., Allen, H.L. and McFee, W.W. (1991a) Fertilization of southern pines at establishment. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 263–277.

Jokela, E.J., McFee, W.W. and Stone, E.L. (1991b) Micronutrient deficiency in slash pine: response and persistence of added manganese. *Soil Science Society of America Journal* 55, 492–496.

Jokela, E.J., Wilson, D. and Allen, J.E. (2000) Early growth responses of slash and loblolly pine following fertilization and herbaceous weed control treatments at establishment. *Southern Journal of Applied Forestry* 24, 23–30.

Jokela, E.J., Dougherty, P.M. and Martin, T.A. (2004) Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long- term experiments. *Forest Ecology and Management* 192, 117–130.

Jokela, E.J., Martin, T.A. and Vogel, J.G. (2010) Twenty-five years of intensive forest management with southern pines: important lessons learned. *Journal of Forestry* 108, 338–347.

Jordan, L., Clark III, A., Schimleck, L.R., Hall, D.B. and Daniels, R.F. (2008) Regional variation in wood specific gravity of planted loblolly pine in the United States. *Canadian Journal of Forest Research* 38, 698–710.

Keeves, A. (1966) Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the southeast of South Australia. *Australian Forestry* 30, 51–63.

Klepac, J., Rummer, B. and Thompson, J. (2011) Harvesting small trees for bioenergy. In: *Proceedings of the 34th Council on Forest Engineering Meeting*. June 2011, Quebec City, Quebec, 11 pp.

Koch, P. (1980) Concept for southern pine plantation operation in the year 2020. *Journal of Forestry* 78(2), 78–82.

Kyle, K.H., Andrews. L.J., Fox, T.R., Aust, W.M., Burger, J.A. and Hansen, G.H. (2005) Long-term impact of drainage, bedding, and fertilization on growth of loblolly pine (*Pinus taeda* L.) in the Coastal Plain of Virginia. *Southern Journal of Applied Forestry* 29, 205–214.

Landsberg, J.J. and Waring, R.H. (1997) A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* 95, 209–228.

Landsberg, J.J., Johnsen, K.H., Albaugh, T.J., Allen, H.L. and McKeand, S.E. (2001) Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *Forest Science* 47, 43–51.

Leggett, Z.H. and Kelting, D.L. (2006) Fertilization effects on carbon pools in loblolly pine plantations on two upland sites. *Soil Science Society of America Journal* 70, 279–286.

Li, B., McKeand, S. and Weir, R. (1999) Tree improvement and sustainable forestry – impact of two linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. *Forest Science* 47, 77–82.

Li, L., Zhou, Y., Cheng, X., Sun, J., Marita, J.M., Ralph, J. and Chiang, V.L. (2003) Combinatorial modification of multiple lignin traits in trees through multigene cotransformation. *The Proceedings of the National Academy of Sciences* USA 100, 4939–4944.

Little, E.L. Jr and Critchfield, W.B. (1969*) Subdivisions of the Genus* Pinus *(Pines)*. US Dept. of Agriculture Forest Service Miscellaneous Publication No. 1144, 51 pp.

Long, A.J. (1991) Proper planting improves performance. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 303–320.

Lowery, R.F. and Gjerstad, G.H. (1991) Chemical and mechanical site preparation. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 251–261.

Ludovici, K.H., Zarnoch, S.J. and Richtor, D.D. (2002) Modeling *in-situ* pine root decomposition using data from a 60-year chronosequence. *Canadian Journal of Forest Research* 32, 1675–1684.

Maier, C.A. and Johnsen, K.H. (2010) Quantifying carbon sequestration in forest plantations by modeling the dynamics of above- and below-ground C pools. *Proceedings of the 14th Biennial Southern Silviculture Research Conference,* General Technical Report SRS–121, US Department of Agriculture, Forest Service, Southern Research Station, Asheville, North Carolina, pp. 3–8.

Maier, C.A., Johnsen, K.H., Dougherty, P., McInnis, D., Anderson, P. and Patterson, S. (2012) Effect of harvest residue management on tree productivity and carbon pools during early stand development in a loblolly pine plantation. *Forest Science* 58, 430–445.

Martin, T.A. and Jokela, E.J. (2004) Stand development and production dynamics of loblolly pine growing on spodosols in north-central Florida USA. *Forest Ecology and Management* 192, 39–58.

Matney, T.G. and Farrar, R.M. Jr (1992) A thinned/unthinned loblolly pine growth and yield simulator for planted cutover site-prepared land in the mid-gulf South. *Southern Journal of Applied Forestry* 16, 70–75.

Matney, T.G. and Hodges, J.D. (1991) Evaluating regeneration success. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 321–331.

McKeand, S.E., Crook, R.P. and Allen, H.L. (1997) Genotypic stability effects on predicted family responses to silvicultural treatments in loblolly pine. *Southern Journal of Applied Forestry* 21, 84–89.

McKeand, S.E., Grissom, J.E., Handest, J.A., O'Malley, D.M. and Allen, H.L. (2000) Responsiveness of diverse provenances of loblolly pine to fertilization – age 4 results. *Journal of Sustainable Forestry* 10, 87–94.

McKeand, S., Mullin, T., Byram, T. and White, T. (2003) Deployment of genetically improved loblolly and slash pine in the South. *Journal of Forestry* 101(3), 32–37.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B. and Catts, G.P. (2006a) What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry* 104, 352–358.

McKeand, S.E., Jokela, E.J., Huber, D.A., Byram, T.D., Allen, H., Lee Li, B. and Mullin, T.J. (2006b) Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. *Forest Ecology and Management* 227, 178–184.

McKendry, P. (2002a) Energy production from biomass (Part 1): overview of biomass. *Bioresource Technology* 83, 37–46.

McKendry, P. (2002b) Energy production from biomass (Part 3): gasification technologies. *Bioresource Technology* 83, 55–63.

McKinley, C.R., Lowe, W.J. and van Buijtenen, J.P. (1982) Genetic improvement of wood specific gravity in loblolly pine (*P. taeda*) and its relation to other traits. In: *Proceedings TAPPI R&D Division Conference*, Asheville, North Carolina, pp. 153–158.

Meadows, S., Gallagher, T. and Mitchell, D. (2011) A new slash bundling concept for use in a southern US logging system. *Forest Products Journal* 61, 210–215.

Miller, J.H., Zutter, B.R., Zedaker, S.M., Edward, M.B. and Haywood, J.D. (1991*)* A regional study on the influence of woody and herbaceous competition on early loblolly pine growth. *Southern Journal of Applied Forestry* 15, 169–179.

Miller, J.H., Zutter, B.R., Zedaker, S.M., Edwards, M.B. and Newbold, R.A. (2003) Growth and yield relative to competition for loblolly pine plantations to midrotation – a southeastern United States regional study. *Southern Journal of Applied Forestry* 27, 1–16.

Mitchell, D. (2006) Perspectives on woody biomass fuel value and specifications in Alabama. *American Society of Agricultural and Biosystems Engineers Paper* 06-8050, St Joseph, Michigan, 7 pp.

Mohan, D., Pittman, C.U. Jr and Steele, P.H. (2006) Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy and Fuels* 20, 848–889.

Morris, L.A. and Campbell, R.G. (1991) Soil and site potential. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 183–206.

Morris, L.A. and Lowery, R.F. (1988) Influence of site preparation on soil conditions affecting seedling establishment and early growth. *Southern Journal of Applied Forestry* 12, 170–178.

Morris, L.A., Pritchett, W.L. and Swindel, B.F. (1983) Displacement of nutrients into windrows during site preparation of a flatwoods forest soil. *Soil Science Society of America Journal* 47, 951–954.

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M. and Ladish, M. (2006) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology* 96, 673–686.

Munsell, J.F. and Fox, T.R. (2010) An analysis of the feasibility for increasing woody biomass production from pine plantations in the southern United States. *Biomass and Bioenergy* 34, 1631–1642.

Murphy, G., Firth, J.G. and Skinner, M.F. (2004) Long-term impacts of forest harvesting related soil disturbance on log product yields and economic potential in a New Zealand forest. *Silvae Fennica* 38, 279–286.

Nairn, C.J. and Haselkorn, T. (2005) Three loblolly pine CesA genes expressed in developing xylem are orthologous to secondary cell wall CesA genes of angiosperms. *New Phytologist* 166, 907–915.

Nambiar, E.K.S. (1996) Sustained productivity of forests is a continuing challenge to forest science. *Soil Science Society of America Journal* 60, 1629–1642.

Nelson, C.D. and Johnsen, K.H. (2008) Genomic and physiological approaches to advancing forest tree improvement. *Tree Physiology* 28, 1135–1143.

Nelson, L.R. and Cantrell, R.L. (2002) *Herbicide prescription manual for southern pine management*. Clemson University Extension Document EC 659, 53 pp.

Novaes, E., Kirst, M., Chiang, V., Winter-Sederoff, H. and Sederoff, R. (2010) Lignin and biomass: a negative correlation for wood formation and lignin content in trees. *Plant Physiology* 154, 555–561.

Panshin, A.J. and de Zeeuw, C. (1980) *Textbook of Wood Technology*. McGraw-Hill, New York, 722 pp.

Peter, G.F. and Neale, D.B. (2004) Molecular basis for the evolution of xylem lignification. *Current Opinion in Plant Biology* 7, 737–742.

Peter, G.F., White, D.E.W., De la Torre, R., Singh, R. and Newman, D. (2007) The value of forest biotechnology: a cost modeling study with loblolly pine and kraft linerboard in the southeastern USA. *International Journal of Biotechnology* 9, 415–435.

Pettersen, R.C. (1984) The Chemical Composition of Wood. In: Rowell, R.M. (ed.) *The Chemistry of Solid Wood*. The American Chemical Society, Washington, DC, pp. 57–126.

Phanphanich, M. and Mani, S. (2009) Drying of pine residues. *BioResources* 5(1), 108–121.

Pletka, R., Brown, R.C. and Smeenk, J. (2001) Indirectly heated biomass gasification using a latent heat ballast: 1. Experimental evaluations. *Biomass Bioenergy* 20(4), 237–325.

Powers, R.F. (1999) On the sustainable productivity of planted forests. *New Forests* 17, 263–306.

Powers, R.F., Scott, D.A., Sanchez, F.G., Volset, R.A., Page-Dumroese, D., Elioff, J.D. and Stone, D.M. (2005) The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220, 31–50.

Prestemon, J.P. and Abt, R.C. (2002) Timber products supply and demand. In: Wear, D.N. and Greis, J.G. (eds) *The Southern Forest Resource Assessment*. USDA Forest Service, General Technical Report SRS-53, Asheville, North Carolina, pp. 299–325.

Pritchett, W.L. and Comerford, N.B. (1982) Long-term response of phosphorus fertilization on selected southern Coastal Plain soils. *Soil Science Society of America Journal* 46, 640–644.

Proe, M.F. and Dutch, J. (1994) Impact of whole-tree harvesting on second rotation growth of Sitka Spruce: the first 10 years. *Forest Ecology and Management* 66, 39–54.

Resende, M.F.R., Munoz, P., Acosta, J.J., Peter, G.F., Davis, J.M., Grattapaglia, D., Resnede, M.D.V. and Kirst, M. (2012) Accelerating the domestication of trees using genomic selection: accuracy of prediction models across ages and environments. *New Phytologist* 193, 617–624.

Retzlaff, W.A., Handest, J.A., O'Malley, D.M., McKeand, S.E. and Topa, M.A. (2001) Whole-tree biomass and carbon allocation of juvenile trees of loblolly pine (Pinus taeda): influence of genetics and fertilization. *Canadian Journal of Forest Research* 31, 960–970.

Roth, B.E., Jokela, E.J., Martin, T.A., Huber, D.A. and White, T.L. (2007) Genotype × environment interactions in selected loblolly and slash pine plantations in the southeastern United States. *Forest Ecology and Management* 238, 175–188.

Sampson, D.A., Wynne, R.H. and Seiler, J.R. (2008) Edaphic and climatic effects on forest stand development, net primary production, and net ecosystem productivity simulated for Coastal Plain loblolly pine in Virginia. *Journal of Geophysical Research* 113, G01003, doi:10.1029/2006JG000270.

Samuelson, L.J., Johnsen, K. and Stokes, T. (2004) Production, allocation and stemwood growth efficiency of *Pinus taeda* L. stands in response to 6 years of intensive management. *Forest Ecology and Management* 192, 59–70.

Samuelson, L.J., Butnor, J., Maier, C., Stokes, T.A., Johnsen, K. and Kane, M. (2008) Growth and physiology of loblolly pine in response to long-term intensive management: defining growth potential in the southeastern United States. *Canadian Journal of Forest Research* 38, 721–732.

Sanchez, F.G. (1998) Soil organic matter and soil productivity: Searching for the missing link. In: Mickler, R. and Fox, S. (eds) *The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment*. Springer-Verlag, New York, pp. 543–556.

Sanchez, F.G., Scott, D.A. and Ludovici, K.H. (2006) Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. *Forest Ecology and Management* 227, 145–154.

Sands, P.J. and Landsberg, J.J. (2002) Parameterization of 3-PG for plantation grown *Eucalyptus globulus*. *Forest Ecology and Management* 163, 273–292.

Schultz, R.P. (1997) *Loblolly Pine: the ecology and culture of loblolly pine (*Pinus taeda *L.)*. Agriculture Handbook 713, US Department of Agriculture, Forest Service, Washington, DC, 493 pp.

Shevchenko, S.M., Chang, K., Dick, D.G., Gregg, D.J. and Saddler, J.N. (2001) Structure and properties of lignin in softwoods after SO_2-catalyzed steam explosion and enzymatic hydrolysis. *Cellulose Chemical Technology* 35, 487–502.

Smith, W.D. and Strub, M.R. (1991) Initial spacing: how many trees to plant. In: Duryea, M.L. and Dougherty, P.M. (eds) *Forest Regeneration Manual*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 281–289.

Stubbs, J., Roberts, D.R. and Outcalt, K.W. (1984) *Chemical Stimulation of Lightwood in Southern Pines*. USDA Forest Service General Technical Report SE-25, 54 pp.

Studer, M.H., DeMartini, J.D., Davis, M.F., Sykes, R.W., Davison, B., Keller, M., Tuskan, G.A. and Wyman, C.E. (2011) Lignin content in natural *Populus* variants affects sugar release. *Proceedings of the National Academy of Sciences USA* 108, 6300–6305.

Sullivan, A.D. and Clutter, J.L. (1972) A simultaneous growth and yield model for loblolly pine. *Forest Science* 18, 76–86.

Sykes, R., Li, B., Isik, F., Kadla, J. and Chang, H.-M. (2006) Genetic variation and genotype by environment interaction of juvenile wood properties in loblolly pine (*Pinus taeda* L.). *Annals of Forest Science* 63, 897–904.

Taherzadeh, M.J. and Keikhosro, K. (2007) Acid-based hydrolysis processes for ethanol from lignocellulosic materials: a review. *BioResources* 2, 472–499.

Vance, E.D., Maquire, D.A. and Zalesny, R.S. Jr (2010) Research strategies for increasing productivity of intensively managed forest plantations. *Journal of Forestry* 108, 183–192.

Vergara, R., White, T.L., Huber, D.A., Shiver, B.D. and Rockwood, D.L. (2004) Estimated realized gains for first-generation slash pine (*Pinus elliottii* var. *elliottii*) tree improvement in the southeastern United States. *Canadian Journal of Forest Research* 34, 2587–2600.

Vergara, R., White, T.L., Huber, D.A. and Schmidt, R.A. (2007) Realized genetic gains of rust resistant selections of slash pine (*Pinus elliottii* var. *elliottii*) planted in high rust hazard sites. *Silvae Genetica* 56, 231–242.

Visser, R. and Stampfer, K. (2003) Tree-length system evaluation of second thinning in a loblolly pine plantation. *Southern Journal of Applied Forestry* 27(2), 77–82.

Vogel, J.G. and Jokela, E.J. (2011) An examination of micronutrient limitations in two young managed southern pine stands planted on Florida spodosols. *Soil Science Society of America Journal* 75, 1117–1124.

Vose, J.M. and Allen, H.L. (1988) Leaf area, stemwood growth, and nutrition relationships in loblolly pine. *Forest Science* 34, 547–563.

Wakeley, P.C. (1954) *Planting the Southern Pines*. USDA Agricultural Monograph No. 18, Government Printing Office, Washington, DC, 233 pp.

Wakeley, P.C. (1969) Results of southern pine planting experiments established in the middle twenties. *Journal of Forestry* 67, 237–241.

Walawender, W.P. and Geyer, W.A. (1988) Influence of tree species and wood deterioration on downdraft gasifier performance. *Biomass* 17, 51–64.

Watson, W.F., Stokes, B.J. and Savelle, I.W. (1986) Comparisons of two methods of harvesting biomass for energy. *Forest Products Journal* 36(4), 63–68.

Wei, L., Thomasson, J.A., Bricka, R.M., Sui, R., Wooten, J.R. and Columbus, E.P. (2009) Syn-gas quality evaluation for biomass gasification with a downdraft gasifier. *Transactions of the American Society of Agricultural and Biological Engineers* 52(1), 21–37.

Wenzl, H.F.J. (1970) Further destructive processing of wood. In: *The Chemical Technology of Wood*. Academic Press, New York, pp. 253–270.

Westbrook, M.D., Greene, W.D. and Izlar, R.L. (2007) Utilizing forest biomass by adding a small chipper to a tree-length southern pine harvesting operation. *Southern Journal of Applied Forestry* 31(4), 165–169.

White, E.M. (2010) *USDA Forest Service, Pacific*. *Woody Biomass for Bioenergy and Biofuels in the United States – A briefing paper*. Northwest Research Station General Technical Report PNW-GTR-825, 45 pp.

White, R.H. (1987) Effect of lignin content and extractives on higher heating value of wood. *Wood and Fiber Science* 19, 446–452.

Yeh, T.-F., Braun, J.L., Goldfarb, B., Chang H.-M. and Kadla, J.F. (2006) Morphological and chemical variations between juvenile wood, mature wood, and compression wood in loblolly pine (*Pinus taeda* L.). *Holzforschung* 60, 1–8.

Zapata-Valenzuela, J., Isik, F., Maltecca, C., Wegrzyn, J., Neale, D., McKeand, S. and Whetten, R. (2012) SNP markers trace familial linkages in a cloned population of *Pinus taeda* – prospects for genomic selection. *Tree Genetics and Genomes* DOI 10.1007/s11295-012-0516-5.

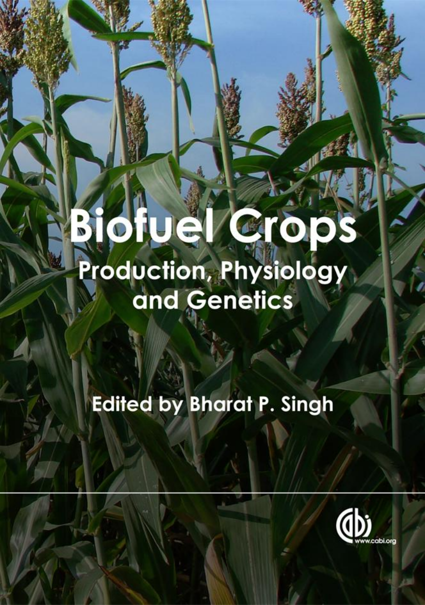
Zhao, D., Kane, M., Borders, B., Subedi, S. and Akers, M. (2012) Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation of 12-year old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. *Canadian Journal of Forest Research* 42, 111–122.

Zhu, J.Y., Pan, X.J., Wang, G.S. and Gleinser, R. (2009) Sulfite pretreatment (SPORL) for robust enzymatic saccharification of spruce and red pine. *Bioresource Technology* 100, 2411–2418.

Zhu, J.Y., Zhu, W., O'Bryan, P.J., Dien, B.S., Tian, S., Gleisner, R. and Pan, X.J. (2010) Ethanol production from SPORL-pretreated lodgepole pine: preliminary evaluation of mass balance and process energy efficiency. *Applied Microbiology and Biotechnology* 86(5), 1355–1365.

Zobel, B.J. and van Buijtenen, J.P. (1989) *Wood Variation, Its Causes and Control*. Springer-Verlag, Berlin, 363 pp.

Zulak, K.G. and Bohlmann, J.J. (2010) Terpenoid biosynthesis and specialized vascular cells of conifer defense. *Integrated Plant Biology* 52, 86–97.



Biofuel Crops

Production, Physiology and Genetics

Edited by Bharat P. Singh

www.cabi.org

Biofuel Crops

Production, Physiology and Genetics

Biofuel Crops

Production, Physiology and Genetics

Edited by

Bharat P. Singh

Fort Valley State University
Fort Valley, Georgia
USA

www.cabi.org

CABI is a trading name of CAB International

CABI
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: info@cabi.org
Website: www.cabi.org

CABI
38 Chauncey Street
Suite 1002
Boston, MA 02111
USA

Tel: +1 800 552 3083 (toll free)
Tel: +1 (0)617 395 4051
E-mail: cabi-nao@cabi.org

A catalogue record for this book is available from the British Library, London, UK.

Library of Congress Cataloging-in-Publication Data

Biofuel crops : production, physiology, and genetics / edited by Bharat P. Singh, Fort Valley State University, Fort Valley, Georgia, USA.
pages cm
Includes bibliographical references and index.
ISBN 978-1-84593-885-7 (hbk)
1. Energy crops. 2. Energy crops--Breeding. 3. Energy crops--Genetics. 4. Biomass energy. I. Singh, Bharat P.

SB288.B57 2013
631--dc23

2013008421

ISBN: 978 1 84593 885 7

Commissioning editor: Claire Parfitt
Editorial assistant: Emma McCann
Production editor: Tracy Head

Typeset by SPi, Pondicherry, India.
Printed and bound in the UK by CPI Group (UK) Ltd, Croydon, CR0 4YY.

Contents