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Woody energy crops in the southeastern United States: Two centuries of practitioner experience☆

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ABSTRACT

Forest industry experts were consulted on the potential for hardwood tree species to serve as feedstock for bioenergy in the southeastern United States. Hardwoods are of interest for bioenergy because of desirable physical qualities, genetic research advances, and growth potential. Yet little data is available regarding potential productivity and costs. This paper describes required operations and provides a realistic estimate of the costs of producing bioenergy feedstock based on commercial experiences. Forestry practitioners reported that high productivity rates in southeastern hardwood plantations are confined to narrow site conditions or require costly inputs. Eastern cottonwood and American sycamore grow quickly on rich bottomlands, but are also prone to pests and disease. Sweetgum is frost hardy, has few pest or disease problems, and grows across a broad range of sites, yet growth rates are relatively low. Eucalypts require fewer inputs than do other species and offer high potential productivity but are limited by frost to the lower Coastal Plain and Florida. Further research is required to study naturally regenerated hardwood biomass resources. Loblolly pine has robust site requirements, growth rates rivaling hardwoods, and lower costs of production. More time and investment in silviculture, selection, and breeding will be needed to develop hardwoods as competitive biofuel feedstock species. Because of existing stands and fully developed operations, the forestry community considers loblolly pine to be a prime candidate for plantation bioenergy in the Southeast.
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1. Background

U.S. Public Law 110-140 mandates that biofuel production increase from 34 hm^3 in 2008 to 136 hm^3 in 2022, including 60.6 hm^3 of "advanced cellulosic biofuel" [1]. The U.S. Department of Energy set goals for cellulosic biofuel and feedstocks, including short-rotation woody crops, that imply a delivered feedstock price below 55 \$ Mg^{-1} [2]. Federal, state, and academic organizations are cooperating through regional partnerships to help address the challenges of bioenergy production [3]. Feedstock partnerships are working to quantify opportunities for feedstock production in each of five

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regions in the continental United States [3,4]. This paper discusses the hardwood growth potential in the southeastern region, an area south and inclusive of Kentucky and Virginia to east Texas.

In the southeastern United States, biomass is presently the most promising renewable-energy resource [5]. Climate and soils favor abundant biomass production, and more than half of the region is covered in forests. More than 80 million hectares of southeastern timberland produce about 60% of U.S. timber products. In addition to forestland, there are more than 2 million hectares of idle farmland in the Southeast that could potentially be converted to woody energy crops [6]. Furthermore, the forest industry is highly developed in this region and already operates efficient pine production on a commercial scale [7,8]. While there is extensive experience with pine in the region, much less experience and data are available on potential productivity for hardwoods.

Hardwoods are of special interest as potential feedstock for a biofuel industry because of their high rates of production, physical characteristics favorable for some energy-conversion processes, and recent progress with genetic mapping [9]. Pine has received less attention as a feedstock for conversion to liquid transportation fuels (e.g., ethanol) because relatively high levels of secondary chemicals in pine create impediments for biochemical conversion. However, traditional and advanced thermochemical conversion facilities in the region [6] suggest the market is favoring thermochemical over biochemical conversion of pine. Choice of feedstock will ultimately depend on price and availability.

Collection of more reliable and consistent information on the potential scale-up of woody crop production for bioenergy, including data on yields, commercial operation costs, and sustainability, is a current priority of the research community [4]. Obtaining high quality data can present many challenges. Monitoring requires several growing seasons before yields can be quantified. Fluctuating markets and public interest make it difficult to maintain commitment for silvicultural prescriptions. These logistic obstacles, as well as inconsistent site conditions, result in highly variable results. Furthermore, available data on hardwood productivity are based primarily on research station sites rather than larger scale, operational experiences, which makes it difficult to draw useful conclusions about commercial woody-energy-crop production potential. Nevertheless, timber companies operating in the region have a rich history in developing hardwood plantation management.

2. Purpose

The present effort sought to record knowledge of industrial practitioners with professional experience in the development of operational hardwood plantations in the southeastern United States. Interviews provided insights on the limitations, opportunities, and potential productivity from hardwoods in the region. Practitioners from forest-product companies have researched the productivity potentials of a range of tree species during the past 50 years. Their combined expertise was applied to assess the potential for hardwood species as energy crops, focusing on the following areas:

- Identifying favorable hardwood energy-crop species for the Southeast
- Identifying what data are available on hardwood productivity in the region
- Providing best estimates of production rates for southeastern hardwoods
- Describing silvicultural practices required to achieve predicted production rates
- Estimating costs of implementing those practices
- Comparing present and projected hardwood productivity rates to standard loblolly pine silviculture as an alternative energy crop
- Assessing data gaps and proposing key areas where further research is required

3. Methods

The approach involved scoping, interviews, compilation, and comparative analysis. The scoping began with identifying practitioners with extensive practical experience growing hardwoods for commercial purposes in the region. This was done through iterative referrals beginning with known experts. Another scoping task was to determine species and key variables to study. The list of species was initially developed from the literature and modified with input from practitioners. A template was developed to provide consistency in covering topics and a standard structure for each interview.

Interviews were conducted from January to May, 2007 with a standard questionnaire. Thirteen practitioners with more than 250 years of aggregate forestry experience in the Southeast were interviewed in seven individual sessions and two group sessions. A mixture of telephone and face-to-face interviews was conducted. Results from each interview were documented and subsequently shared with interviewees, who were invited to review the results and provide corrections and comments. Productivity estimates made by the 13 practitioners were tabulated along with any qualifications from those interviewees.

To compare productivity estimates, it was necessary to qualify environmental and silvicultural practices in a standardized way because site conditions and management practices largely control productivity. Climate in the Southeast was easily defined by geography. Fine-scale site variation was standardized on the basis of soil characteristics. Soils strongly influence the establishment, growth, and productivity of trees and often determine (a) which species are most appropriate for a site and (b) what treatments are necessary. To normalize productivity estimates, soil groupings were selected from the forest-soil classification matrix developed by the Cooperative Research in Forest Fertilization (CRIFF) program at the University of Florida [10]. The CRIFF soil groupings are based on easily recognizable features that can be classified in the field, such as depth to clay and water table. All of the interviewees were familiar with this type of soil classification for stratifying forestland.

Silviculture practices (soil preparation, fertilization, thinning, etc) also affect productivity. To further normalize productivity estimates, a standard silvicultural approach was

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Box 1: Standard Silviculture Practices for Comparing Hardwood Productivity

Site preparation, planting density, and treatment require knowledge of soils and species to be planted. The first essential step is to understand the soil and select an appropriate species and variety for the site. Soils should be tested and treated, if required, to bring pH and nutrients to minimal acceptable ranges at planting. Other steps follow.

a) Site preparation includes clearing debris as necessary; up-soil or chisel plow (in two directions, if needed) to break hardpan; disc or double disc for clean, level planting; form raised beds if high spring moisture will be a problem for the species selected; and treat with appropriate herbicide in season (July-September) prior to planting.

b) Establishment by mechanized planting is preferred to ensure proper depth and good closure; timing is important—one must plant during the late dormant season and at an appropriate time to take advantage of spring rains; targeted herbaceous control should be used for the first two seasons, as needed (usually, targeted control will be needed twice in year one and at least once more in year two) to control competition; and the necessary steps should be taken to avoid drought or flood during the initial year to ensure proper establishment. Typical spacing is 3.7 x 3.7 m in better soils and 2.7 x 2.7 m for upland or poor soils.

c) Monitoring and management include inspection and control for pests and competition and verification that growth targets are being met (and if not, determining why); depending on site and species, one additional fertilizer treatment is often recommended at mid-rotation (5 to 8 years; typically 110 kg ha-1 of N but actual composition could vary for given site conditions; usually at least N is needed)

developed (see Box 1). Practitioners were asked to estimate productivity on the basis of this prescription and to describe any revisions necessary to achieve productivity estimates for each species.

Consistent with the literature [11], all practitioners noted that the eucalypts require far fewer silvicultural inputs, so a parallel but significantly different standard approach was developed for the eucalypts (see Box 2). The standardized set of operations and treatments, combined with the CRIFF soil tables, allowed productivity for different species and sites to be compared in terms of a common baseline for site preparation, stand establishment, weed control, fertilization, etc.

4. Compilation of data

Each interview produced a list of promising species, growing ranges, notable site requirements, costs, and estimates of present and future productivity averaged over a given rotation period. The yields assume that the standard silvicultural practices (Boxes 1 and 2) are followed. The high and low yields

Box 2: Silviculture Practices Typical for Eucalypts

- During site preparation, treat the soil, if required, to bring pH to an acceptable range at planting. Form raised beds if high water will be a problem. Treat with an appropriate herbicide to control weeds during the first year.
- During establishment, mechanized planting is preferred to ensure proper depth and good closure; timing is important—one should plant to take advantage of rains. Use targeted herbaceous weed control as needed. Avoid drought in first year.
- Once established, eucalypts perform well with minimal additional inputs.

reflect a range of typical site conditions that are described for each species. Yields were converted from local units on the assumption that green wood contained 50% moisture on a total mass basis. The responses from all interviewed practitioners were averaged by species as $Mg\,ha^{-1}\,y^{-1}$. Reported results from smaller trials and research data were segregated from large-scale commercial production data. A similar process was used to develop average reported costs in 2006 dollars for plantation establishment and treatments. Costs for implementing the recommended silvicultural practices (Boxes 1 and 2) were estimated, and any exceptions were noted for a given species.

5. Results

The interviews produced several areas of agreement and a few differences of opinion. Every respondent replied to the first query in the standard questionnaire ("What hardwood species is best for biomass production (and where) in the Southeast?") with various forms of, "It depends." Practitioners consistently acknowledged a need to select and improve cultivars for the specific needs of commercial operations, noting that those needs will vary depending on site characteristics, markets, rotation, harvest technology, qualities desired in final products, and other factors. They also agreed that experience with hardwoods was limited and that current commercial productivity is low compared to future potential because there is a lot of room for improvement in management and genetics [8,11–13]. Species that are better understood in terms of cultivar genotypes and traits are more likely candidates for rapid improvement and commercial applications in the near to medium term [9,14,15]. Practitioners believed that the hardwood species best positioned for future commercial production are currently sweetgum for broad regional applications and eucalypts for the coastal zone, where risks of freezing are minimal. Scientific advances with poplar make it a strong potential future feedstock candidate for biochemical conversion, particularly if cultivars are produced to tolerate marginal site conditions [14–16]. Although the interviews focused on hardwoods, practitioners consistently recommended that loblolly pine be given more consideration as a potential bioenergy feedstock. Indeed, despite the specificity of the initial question, "What is the best hardwood species for biomass in the Southeast?", many of the respondents

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Table 1 – Mean annual production by species in megagrams of dry equivalent stem weight per hectare-year: aggregate interview responses.

Species	Dry Mg ha^{-1} y^{-1}		
	Low	High	Average
Mixed upland hardwoods	1	4	3
Mixed bottomland hardwood	7	9	8
Oak, upland	2	4	3
Cottonwood			
Poplar hybrid trials	9	20	15
Poplar hybrid plantation	3	6	5
Sycamore	7	11	9
Sweetgum trials	7	12	9
Sweetgum	4	8	6
Aspen hybrids	9	12	10
Eucalyptus (average of various species)	18	25	22
Loblolly pine	8	10	9

answered, "Why not pine?" underscoring their belief that the prevalence of pine plantations in the Southeast and the broad accumulated knowledge about the management of those plantations [12] made that species a prime candidate for biofuel feedstock production.

The uncertain structure of developing bioenergy markets was a regular discussion point with practitioners because bioenergy crop specifications are dependent on conversion technologies. Many participants believed that there was not yet enough information on desired feedstock characteristics to make a well-founded recommendation for a preferred hardwood species for biofuels.

Table 1 presents the aggregate interview responses for yields. These yield values were determined by asking the respondents to provide their experience-based estimates of productivity of each species, as constrained by a standard set of assumed silviculture practices and the preferred soil range from the CRIFF soil tables (preferred and tolerable soil ranges varied somewhat from species to species). The respondents were asked for a range (low, high, average) that they had experienced for each species. All the lows cited by the individual respondents for a given species were averaged to get the average "low" estimate for that species shown in Table 1. A similar procedure was followed to determine the "average" and "high" estimates for each species.

Estimated yields for eucalypts stand out in terms of growth potential but are based on relatively limited operations in Florida. Trial results with hybrids also appear promising but differ greatly from larger scale experiences. The narrow gap between trials and plantations for sweetgum relative to poplar demonstrates why practitioners favor this species as more reliable across the Southeast.

Table 2 summarizes descriptive information, including geographic range, advantages, and limitations, for each species. Additional information brought forward by the practitioners is summarized below by species.

5.1. *American sweetgum* (Liquidambar styraciflua *L.*)

American sweetgum, also known as redgum and liquidambar, is a medium to large tree adapted to a wide range of soils. It is one of the most common southern hardwoods. Its range includes Kentucky, Tennessee, Virginia, and North Carolina except for the higher elevations of the Appalachian Mountains and it extends into northern Florida and eastern Texas with the exception of coastal Louisiana. Sweetgum is tolerant of sites with low moisture and nutrient availability [17] but grows best in moist, somewhat acidic loam or clay soils and has moderate salt tolerance. Commercial planting is found primarily in mid-coastal plains north of Florida from east Texas to Virginia. Survey participants ranked sweetgum as a top choice among current hardwood species for potential commercial bioenergy production because of robust site requirements and despite its relatively low growth rate in comparison to other candidate species. Production rates quoted by practitioners are comparable to those reported in the literature [18]. Some experts estimated that future sweetgum growth rates could nearly double with genetic improvements and better silviculture. Sweetgum requires less management attention and inputs than other hardwoods but it is not recommended for very short rotations because growth during the first few years is slow [19].

5.2. *Eastern cottonwood* (Populus deltoides *Bartr.*)

Eastern cottonwood is a fast growing poplar and one of the largest North American hardwood natives. In natural conditions, cottonwood is often found where seasonal-flood-replenished nutrients aid seedling establishment, rooting of fallen branches, and rapid growth and development. Plantation cultivation in the Southeast requires intensive site preparation and management during the establishment stage for acceptable survival [8]. Site requirements currently limit maximum production to mesic, nutrient rich, bottomlands. Cottonwood's breeding potential offers great opportunities for developing site-adapted genotypes [20]. High initial growth rates tend to taper off after 4–8 years, offering a potential for short-rotation harvests, but constraints of suitable soils and pest susceptibility limit widespread commercial application.

5.3. *Hybrid poplar* (Populus trichocarpa *Torr. & Gray* x deltoides)

Populus is a large and well-studied genus including cottonwoods, poplars, and aspens. The Interamerican Poplar (*Populus trichocarpa x deltoides*) or "T × D" hybrids have been the most successful in hardwood plantations in the northern half of the southeastern region and share many of the characteristics of cottonwood. Further work is needed to develop suitable clones for the Southeast. Euroamerican hybrids (*P. deltoides* × *nigra* L.) and Eurasian hybrids (*P. nigra* × *maximowiczii* A. Henry) have not met notable success in the southeastern United States because of putative (but poorly documented) disease susceptibility. *P. trichocarpa* is currently the only tree species with complete genetic sequencing [9]. Researchers hope this sequencing will facilitate more rapid development of clones with desired traits for bioenergy [14]. However, productivity has generally been lower than expected in plantations partly because of pest and disease problems, as well as a requirement for high site resource availability.

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Table 2 – Range, advantages, and limitations for commercial biomass tree species in the southeastern United States.

Species	Preferable Range	Advantages	Limitations
Sweetgum	Uplands throughout the Southeast	+ Native species + Most adaptable hardwood across region + Fairly well known/studied + Improvement likely in medium term	– Moderate productivity – Limited commercial experience
Eucalypts	Florida and South Coastal Plain (hardiness zone 8b or higher to reduce freeze damage)	+ Highest growth rates + Adaptable to marginal sites + Multiple products/markets + Improvement likely in near term	– Exotic species – Frost vulnerable – Water requirements
Cottonwood and poplar hybrids	Alluvial bottomlands and low river terraces	+ Potential for high growth rates under right conditions + Extensive genetic research + Existing commercial stands + Improvements likely in medium term	– Narrow site requirement – Variable productivity – Requires intensive management and inputs – Not drought tolerant
Sycamore	Well drained bottomlands	+ Fast growing first 2 to 3 years (but not a recommended species with current cultivars)	– Narrow site requirement – Chronic disease problems – Not drought tolerant
Oak (red, cherry bark, and black)	Upland sites in cooler zones (hardiness zone 8 - north)	+ Native adapted to marginal soils + High-value products with biomass as residue + Can outperform others on sites with shallow topsoil and heavy subsoil.	– High costs of initial establishment – Slow growth – Limited data on genetics and silviculture – No commercial experience
Hybrid aspen	Upland sites in cooler zones (hardiness zone 8 - north)	+ High growth potential + Tolerant to range of sites, pH, drought	– Requires more study – In early stages of research
Willow, river birch, red maple, yellow poplar, and others	To be determined	+ Potentially fast growing + To be determined	– Relatively unknown in the Southeast – Research needed
Mixed natural hardwoods	Existing stands throughout region	+ More than 53 × 106 hectares of mature stands accessible and harvestable + Mixed products and markets + No establishment or cultivation costs	– Heterogeneous sizes, types, etc. complicate harvest and market options – Typical access more costly and difficult
Loblolly pine	Established pine plantations and native pine areas throughout region	+ Well developed operations (50+ years of intense R&D) with 13 × 106 hectares in the southeastern United States + Better productivity than most hardwoods on same sites + Broad genetic potential + Improvements ongoing	– Undesired traits for biochemical conversion to ethanol

5.4. *American sycamore (*Platanus occidentalis *L.)*

American sycamore grows rapidly with the range of production rates quoted by practitioners supported by properly managed experimental trials [21]. Its native distribution is primarily confined to riparian areas with high resource availability in the eastern half of the United States. The ideal range for sycamore is limited because of susceptibility to *xylella* (Pierce's disease for grapes), *ceratocystis*, and anthracnose disease (*Apiognomonia veneta*, syn. *Gnomonia platani*, a family of introduced fungal blights) [22]. Practitioners explained that plantations will perform best in alluvial bottomlands in Tennessee and Virginia, north of the hazard line for *xylella* (roughly, from USDA plant hardiness zone 6 northward). Initial efforts to breed disease resistance with hybrids have not been sustained and, therefore, have not

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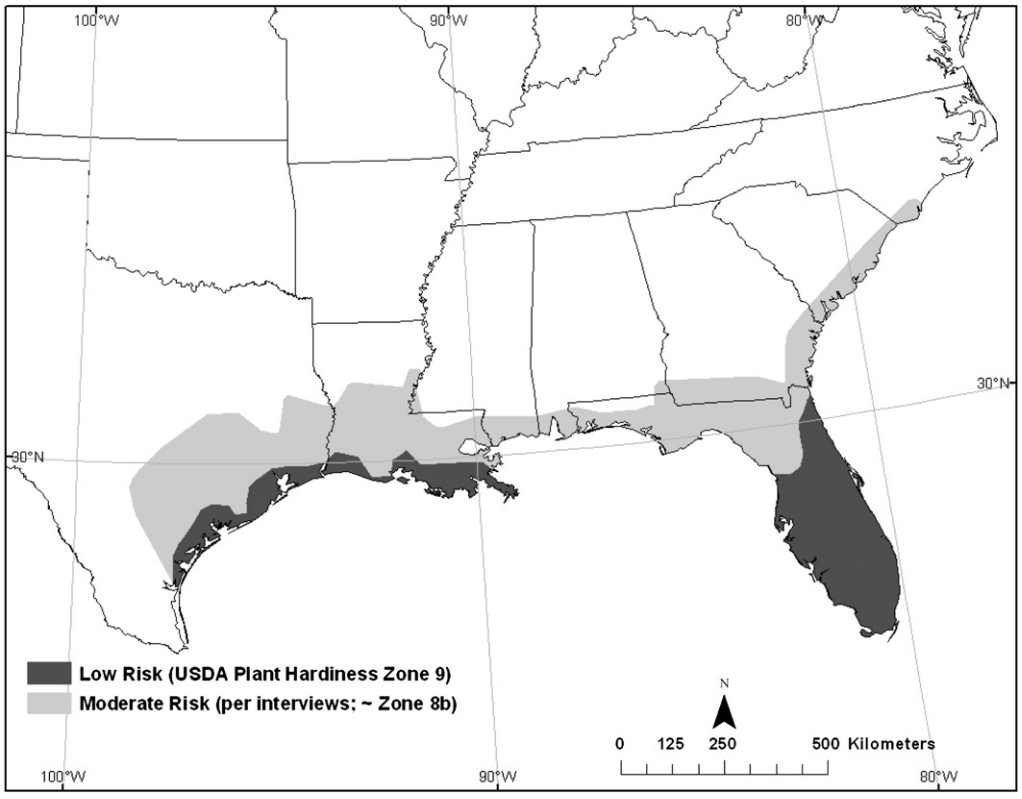

Fig. 1 – The geographic range recommended for eucalypts depended on variety and purpose. To reduce the risk of frost when managing longer rotations for larger stems, a frost free range that roughly coincides with USDA Plant Hardiness Zone 9 was recommended (dark shading). Biomass production for energy was expected to be viable with short rotations extending farther north into Hardiness Zone 8 (light shading). Source: ORNL figure derived from practitioner interviews and Plant Hardiness Zones for the Southeast from the U.S. National Arboretum [50].

achieved desired results in plantation settings. Sycamore requires intensive site preparation; but once it is established, leaf mulch helps control weeds and hold moisture. Its high initial growth rates permit rapid biomass production, especially under short coppiced rotation [19,20].

5.5. *Eucalypts*

Eucalypts are natives to Australia and Asia belonging to three closely related genera: *Eucalyptus* L'Her., *Corymbia* Hill & John., and *Angophora* Cav. More than 700 species are in the *Eucalyptus* genera alone, ranging from tall forest trees to short shrubs. Current varieties of eucalypts perform well on moderately well and well drained sites in areas free of frost (see Fig. 1). Eucalypts' growth rates fluctuate with water (and therefore nutrient) availability. When nutrient supply is low, growth can slow to a static state. During periods of high water and nutrient availability, eucalypts' growth rate will surge if the temperature is favorable, resulting in high productivity [23]. Eucalyptus growth and productivity are closely tied to water use, with productivity varying inversely with evaporative demand when growth was not limited by water or nutrient deficit [24]. Eucalypts require minimum phosphorus fertilization but otherwise do well on nutrient-poor soils and can adapt to a wide range of pH. Eucalypts are susceptible to damage from cold temperatures because frost depresses maximum net photosynthesis, although eucalypt clones have been developed with increased frost (but not freezing) resistance. Moreover, because it takes several days for eucalypts to recover from a frost event, the effects of repeated (e.g., diurnal) frosts are cumulative and can produce greater and greater damage [25].

Eucalypts have been established successfully on Florida land degraded by phosphate mining [26]. They do best with proper site preparation, but require less input for establishment than do other hardwoods (see Box 2). In current commercial operations, eucalypts are often planted like loblolly pine in bedded rows about 3 m apart and spaced at 1.8- to 2-m intervals, resulting in about 200–280 trees ha^{-1}. New clones are being selected for high productivity on a broad range of sites and soil conditions with the hope of achieving 30 dry Mg ha^{-1} y^{-1} in appropriate sites within the next decade [27]. Clone cuttings are easy to reproduce and some varieties (*Corymbia torelliana* and *E. amplifolia*) are reported by practitioners to permit year-round coppicing with good recovery, an unusual and desirable trait. The University of Florida is releasing selected *Eucalyptus grandis* cultivars, and the State of Florida is supporting development of *Eucalyptus* plantations for bioenergy [28].

5.6. *Other species*

Practitioners cited several species that have been considered and/or tested because of high growth potential but, at this time, are considered less desirable than those species listed

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above for commercial plantation production in the Southeast. Production rates in this region are largely undocumented for these less-desirable species, which include:

- Red maple (because of difficult silviculture),
- Locust (unimpressive growth and lack of market), and
- River birch (lack of market, multi-stemmed, but could merit further study for bioenergy).

However, the practitioners also identified several species that merit further study to better estimate their potential in future biomass production systems, especially within upland sites north of eucalypts' current range. Among those species warranting more study, hybrid aspen (*Populus alba* L. *x tremula* L.) offers potential north of hardiness zone 9 in poorly drained to well drained soils. Hybrid aspen reportedly tolerates a range of pH and drought, and initial research reported by practitioners led to their estimates that site-appropriate selection offers growth rates of 9–12 dry Mg ha^{-1} y^{-1}. Documentation of hybrid aspen performance in the southeastern United States is not available; however, significant genetic variations that have been induced by environmental interactions in other regions [29] suggest that yields could increase significantly with genetic improvements.

Oak (*Quercus* L.) has received minimal attention for potential genetic improvement and improved silviculture in the southeastern United States. Several varieties, such as *Q. falcate* (red), *Q. velutina* (black) and *Q. falcate var. pagodaefolia* (cherry bark), appear to show promise for relatively rapid growth on appropriate sites [30]. Because oak is highly valued by sawmills, there may be more economic incentive to grow it for multiple products and markets with tops and residues allocated to bioenergy. At present, difficulties and costs to establish oak plantations appear to be major hurdles. Oak silviculture is considered to be more difficult than that of sweetgum or eucalypts because seeds and seedlings are larger and harder to store, handle, and manage and because oak's growth is initially very slow, leading to high costs for establishment, controlling competition, and monitoring young plantations.

Yellow poplar (*Liriodendron tulipifera* L.) is also known as "tulip poplar". This native to eastern North America grows much faster than sweetgum in some sites but prefers better drained soils and cove-settings in upper coastal plains (northern Alabama and Tennessee). It does not withstand inundation but requires adequate water during summer months to maintain growth. Productivity is somewhat unpredictable but it may be an option that merits consideration on selected upland loamy soils.

Willow (*Salix* L.) is a genus including 400 species and many hybrids. Although there are species native to the region, willow has received minimal study in the Southeast. Given its promising productivity in other regions, very efficient coppice production systems [31,32], and wide native distribution, it merits further study in the southeastern United States.

Southern pine sustains the world's largest plantation forestry operations. The practitioners surveyed had vast experience and knowledge about pine plantations and expressed a number of reasons why loblolly and slash pine should be considered as a regional bioenergy feedstock. Pine productivity in the Southeast is documented elsewhere [33–36]. Several experts in separate interviews spontaneously questioned the focus on hardwoods and argued that pine should be a top biofuel feedstock candidate in the region because:

- There are 13 million hectares of pine plantations in the Southeast, and 600,000 ha are planted each year.
- The germplasm data bank for southern pine is unrivaled by other species.
- Southern pine productivity has risen by a factor of 4 during the past 60 years [7], and an additional factor-of-4 increase is possible from genetic improvement and intensified management.

Loblolly (*Pinus taeda* L.) is capable of rapid growth on a wide range of sites, while slash pine (*Pinus elliottii*) is also very productive, but has somewhat narrower site requirements. Loblolly and slash pine grow on soils that range from very poorly drained to moderately well drained. Commercial loblolly plantations typically produce from 1 to 5 Mg ha^{-1} y^{-1} dry stem biomass, while demonstrated potential under intensive management is 5–12 Mg ha^{-1} y^{-1} [18,35].

5.7. *Natural hardwoods and mixed-stand management*

Natural mixed-hardwood stands have average growth rates of about 3 dry Mg ha^{-1} y^{-1} in upland sites and 8 dry Mg ha^{-1} y^{-1} in river bottoms [37]. Estimating mixed hardwood productivity is complex but long-term monitoring of permanent plots in the Southeast has facilitated the development of yield models for the region [37,38]. There are about 55 million hectares of natural hardwood stands already growing, available, and accessible for collection [39] if the market for the relatively low density of heterogeneous products justified the costs of harvest, handling and transport. These forests could be much more productive and valuable with small investments in silviculture [40,41]. For bioenergy feedstock, questions about composition from mixed species remain to be answered; but if processes do not require homogenous feedstock, natural forests offer an option to increase biomass supplies more quickly and with lower costs than by establishing new hardwood plantations and waiting a period of years before harvest.

Natural upland forests left to grow 60 years produce 134 dry Mg ha^{-1} and are economically viable to harvest [37]. On average, they offer about a 7% internal rate of return on minimal investment and costs. The most economical management approach is to clear-cut and then generate another even-aged forest, although social and environmental considerations may limit this option. No treatments are required because natural mixed hardwoods come back voluntarily. However, there are opportunities to dramatically increase value and productivity with timed selective thinning and fertilizer [37]. The silvicultural concept is to speed up the self-thinning that a natural stand would follow for selected (most desirable) species and stems [37,42]. Significant stand improvement is possible through early interventions (the first 1–15 years), selectively removing lesser value stems to release higher value trees. Forest thinning procedures for improved stand structure and fuel reduction (wildfire mitigation) could generate a low-cost source of biomass feedstock [43].

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6. Impediments to hardwood plantations

Practitioners agreed that current hardwood varieties did not appear economically viable for plantation production in the Southeast, with the exception of eucalypts in a restricted range. Many of the hardwood plantations established during the past two decades have not been managed according to standard silviculture guidelines because the management costs could not be justified.

6.1. Markets

The biggest hurdle for hardwood plantations is economics. Costs, discussed below, are relatively high compared to demand and price incentives. There is not a plausible near-term scenario with prices that justify a land owner's investing significant funds in establishing a hardwood plantation for biofuel alone, given the existing supply potential from other sources (residues, wastes, and existing mixed stands). Without strong market signals, it is difficult to justify the large fixed investments and ongoing costs for management over several years before any return is possible. The region already harvests 70–80 Tg y^{-1} on a dry basis for pulp and paper [44] in addition to volumes of hardwoods for poles and other timber products, offering potential for conversion or integration and expansion of the existing industry into more diversified products, including bioenergy. If genetic research paired with biofuel-conversion technologies results in specialized tree varieties suited for energy production, it might alter the prognosis. The fact remains that foreseeable prices for energy feedstocks are lower than prices for feedstocks destined for other products, including pulp and timber. Landowners will need incentives or guarantees prior to making large investments in a new crop and technology [43].

6.2. Local regulation and environmental issues

A number of environmental concerns arise regarding woody-energy-crop production systems that may limit deployment through regulation, added costs, or public opposition. Practitioners stated that some woody plants proposed for short-cycle biomass production in Florida faced costly and complex regulatory obstacles associated with State concerns about invasive species. Similarly, there may be resistance to plantations with high water demand in areas where aquifer recharge and water supplies are a concern. For economic benefits to be realized from forest biotechnology, social, environmental and political concerns about risks and dispersion control must be overcome [45]. Other concerns include visual and environmental impacts of harvesting, site degradation through nutrient removal, compaction, and potential hazards from off-site transport of agricultural chemicals. Fulfilling the requirements for sustainable production certification as advocated by many environmental groups may add costs that are not compensated by the marketplace. Environmental issues and public perceptions need to be addressed in early stages of plantation planning to develop proposals that are environmentally sound and supported and accepted by neighboring landowners and citizen groups.

6.3. Lack of silviculture

The most common obstacles to commercial hardwood plantation success mentioned by interviewees, after economics, were related to silviculture: inappropriate site-variety selection, inadequate site preparation, inadequate management to ensure first year establishment, etc. Basic silviculture guidelines such as those summarized in Box 1 must be followed to achieve survival and growth rates in the ranges described in Table 1. Of all silviculture practices, the most often cited as a "showstopper" was the lack of timely weed control [8,19,46]. As one practitioner put it, "Once an observer 'thinks it's time' [to apply weed control products], it's too late." Plus, crews must be well trained and supervised, or they can kill trees with overspray. Ensuring competition control and adequate water for establishment are critical in the first year for several species, including sweetgum and eucalypts. Even species thought to tolerate vegetative competition will show favorable response to herbicide application [47], demonstrating the need for such treatments to maintain growth.

6.4. Disease, herbicides, and site-specific issues

Additional silviculture issues cited as problems were improper planting, moisture problems after planting (too much or too little), improper selection of plant material for site conditions and disease [48]. Recommendations included not moving a variety south of its preferred climate zone because it will likely encounter more pests and disease and being aware of the sensitivity of some species to herbicides (sycamore and cottonwoods have had establishment problems because of residuals from earlier herbicide applications) [46].

7. Costs

Reported costs (expressed in 2006 dollars) varied widely with species, planting density, site conditions, and scale of plantation operations and are embodied largely in establishment, treatment, logging and transport. The ranges of costs reported by practitioners for standard silviculture treatments are presented in Table 3 for different levels of production to illustrate how cost per megagram of biomass is affected by production rate.

7.1. Establishment

Stand establishment includes site preparation, cultivation of soil into beds (if necessary), cost of seedlings, and planting. Establishment represents the primary cost for a commercial plantation and must be discounted over time. Site preparation and the application of fertilizer and pesticides are often mechanized.

For example, on a per-hectare basis, site preparation for hardwoods may include the following average costs: (1) Basic site cultivation often requires sub-soil chisel which will cost about 250 $ for a relatively clean site with good drainage; add another 100–150 $ if the site requires sheering, piling, clearing of debris, leveling etc.; and add 120 $ if bedding is needed. (2) Initial chemical preparation costs can range from 50 to 130 $ as explained below. (3) Seedlings or clones cost 170–250 $. (4)

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Table 3 – Estimated costs of production for selected species in the Southeast United States aggregated from interviews. Any comparisons should be tempered in consideration of the variables and limitations discussed in the text.

		Sweetgum		Cottonwood		Pine	
		Cost range ($ ha^{-1})		Cost range ($ ha^{-1})		Cost range ($ ha^{-1})	
		min	max	min	max	min	max
Year 1	Site preparation	247	494	247	988	124	432
	Planting stock	185	247	185	247	49	99
	Planting	99	124	99	124	99	124
	Herbicide	161	395	161	395	86	173
	Pesticide				86		
Year 2	Herbicide	86	173	86	173		86
	Pesticide			86	86		
Year 3	Pesticide				86		
Year 4	Pesticide				86		
	Fertilize		62		62		62
Year 6	Fertilize		62				
Year 8	Fertilize		62		62		62
Year 10	Fertilize		62				
Year 12	Fertilize		62		62		
Total		778	1742	865	2459	358	1038
Product weight basis ($ Mg^{-1})							
	High productivity	13	27	14	40	6	18
	Low productivity	31	64	34	94	14	41

Fertilizer or soil amendments, if needed, range from 60 to 150 $. (5) Planting costs 100–120 $. Thus, the initial investment to establish a hardwood plantation can run from 690 $ under the least cost scenarios described above up to 1700 $ ha^{-1} under the high-end scenarios.

7.2. *Treatment*

The initial investment in a hardwood plantation could be lost if weeds are not controlled. Herbaceous-weed control is the most critical treatment in the first year of a hardwood plantation, although that action may not be necessary if the prior history of the land included chemical site preparation. Chemical treatments are typically done at least two more times after the initial site preparation and, more typically, three to four times. Each herbaceous weed control treatment can cost from 50 to 130 $ ha^{-1}, depending on site conditions, labor costs and whether it is done manually, mechanically or with aerial spray. Unlike pine and eucalypts, most hardwoods studied require fertilization to achieve the reported productivity targets. Sweetgum, for example, may need fertilizer every other year, beginning in year four. The annual fertilizer treatments can range from 60 to 100 $ ha^{-1}. Assuming a 12–14 year rotation for sweetgum, these treatments – three weed controls and four fertilizations – would cost about 560 $ ha^{-1}.

Thus, the total production expenditures could range from 800 to 2500 $ ha^{-1} for hardwoods. If a plantation produces 5–10 Mg ha^{-1} y^{-1} on a dry basis, the costs could vary from 13 to 100 $ Mg^{-1} produced, with lower productivity being a key factor for the higher unit costs. Harvest and transportation costs need to be added for a total delivered price. The costs of hardwood plantation production have generally run much higher than industry targets for economically viable operations, which fall in the range of 35–45 $ Mg^{-1} delivered [5,43]. Table 3 shows that only a high-yielding plantation would be economically viable given a target delivered price of 55 $ Mg^{-1} [2]. This further underscores the importance of selecting plants with high growth potential for specific site conditions.

The costs for logging and transportation are highly variable, depending on the type of equipment used, tree size, and distance to markets. Estimates for average costs ranged from 5 to 10 $ per green megagram for logging and from 10 to 20 $ for transportation or about double those values per dry megagram.

Note that cost estimates vary significantly by species and site. Some situations may require additional monitoring, care, and treatments. For example, to ensure survival in the first year during a drought, irrigation may be necessary. And some hardwood species are more likely to require pest controls (i.e., against the cottonwood leaf beetle).

The practitioners stated that, on the basis of their experiences and their current expectations about the needs of hardwood plantations, they believed that the system developed for pine would prove to be much more efficient and less costly because pine requires less site preparation, offers readily available and inexpensive seedlings, and requires only one herbaceous weed control after planting. Furthermore, pine offers more predictable production results.

8. Discussion

All the practitioners agreed that the selection of appropriate genetic stock for a given site was crucial. Plantation species and genetics should be adapted to the site conditions and preferably selected from sources that reduce the chances for disease, pest, and hardiness problems. A surprising number of practitioners questioned the research focus on hardwoods, suggesting without a prompt, that loblolly pine was the best-adapted plantation species for biomass in the region. A few practitioners also argued that natural mixed forests should be considered

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and managed for biomass production rather than attempting to apply more costly, conventional plantation systems to hardwoods. These observations reflect the practitioners' qualitative assessments based on their experiences and provide a point of reference for future research. Additional data and resources are required to permit more systematic, quantitative assessments.

The growth rates in Table 1 reflect the practitioners' estimates for productivity while assuming proper silviculture and use of appropriately selected hardwood genetic material for a given site. The high and low productivity estimates reflect variations within a range of suitable sites for a given species. Other published studies have compared growth rates under multiple variables in test plots, including several cases where recommended silviculture is not applied (e.g., no fertilizer or irrigation for establishment). These studies show a range of growth rates that are generally much lower than the estimates in this paper [18,21,35,49]. Likewise, during the past 30 years, several hardwood plantations were established and virtually abandoned with minimal silviculture. The productivity rates for such cases can be expected to regress toward the growth rates of natural forests.

The productivity of hardwoods has a measurable relationship with soil and site qualities. Therefore, with sufficient experience and data, site-productivity tables can be developed for hardwood plantations similar to those that now exist for loblolly pine. Based on many years of trials, the productivity of sweetgum has been predicted to fall somewhat below that of pine in the loblolly belt, assuming current varieties and similar levels of inputs. However, site adaptation for both of these species is similar and much broader than the bottomland species like cottonwood and sycamore.

The current state of the forest products industry casts considerable doubts about the role commercial hardwood forest plantations could play in biofuel feedstock supply in the near or medium term, given existing market prices and supplies. Other biofuel resources, such as urban wastes and residues, are likely to be available at lower cost. In the Southeast, millions of hectares of mature natural hardwood stands could also make it difficult for plantations to compete economically in the near and medium terms. Despite these challenges, most practitioners opined that future hardwood productivity could compete with and exceed pine if more intensive and coordinated research and development investments were applied to hardwood forestry in the region.

Many uncertainties exist regarding preferred characteristics for future biofuel feedstocks. Research is ongoing to define optimal chemical and physical characteristics (sugars, lignin resistance to processing, optimization of by-products, and integrated steps to reduce pre-treatment) in conjunction with improved conversion technologies. Simultaneously, research continues to improve the growth characteristics of several hardwood species [43]. New breakthroughs could change assumptions about what feedstock species would perform best in the region.

The interviews highlighted that many species, including sweetgum, eucalypts, and pine, appear to offer promise for significant improvements in productivity (up to 40% over present average rates) based on traditional varietal selection for a given site. This optimism is based on commercially available technology that could be scaled up in response to market demand. Further improvements in productivity are possible through transgenic efforts to develop hardwood variants that are more drought and disease resistant and cold and herbicide tolerant than are the wild strains or current hybrids. If successful, these efforts could result in significant increases in productivity over the improved varietal yields. Thus, for example, on a site with good soils that currently yields about 9 dry Mg ha^{-1} y^{-1}, growth could increase to 13 Mg ha^{-1} y^{-1} through varietal (sysgenic) work and up to double that (26 Mg ha^{-1} y^{-1}) with transgenic improvements [27]. However, attaining these higher growth rates will most likely also require higher levels of inputs, especially fertilizer.

9. Conclusions

In order to discuss or compare productivity estimates, a standard set of good silviculture practices was required. Failure to follow these practices could have significant impact in terms of both reduced survivability of a stand and much lower yields than predicted here. Experts interviewed agreed that hardwood productivity will vary significantly depending on many factors. Some factors can be controlled or managed to varying degrees (genetic selection, site preparation, and inputs, such as weed control, fertilizer, pest control, and irrigation). Other factors are site-specific and dictate management approaches and the selection of species and varieties best adapted to the location. Soils, drainage, and climate are determining factors for selecting appropriate genetic stock.

Current varieties of fast growing species, such as Eastern cottonwood and American sycamore, are unlikely candidates for large-scale biofuel feedstock production because of disease, narrow site requirements, and the demand for limited bottomland soils. The land most readily available for bioenergy crops occurs in more marginal, upland areas. Sweetgum is tolerant of upland sites, is frost hardy, has few pest or disease problems, and grows across a broad range of sites from Virginia to east Texas. However, experience indicates that sweetgum growth rates are relatively low. Eucalypts require low water and nutrient supply and offer high potential productivity but are limited by frost to a narrow strip of the southern Coastal Plain and Florida.

In terms of present forest resources, pine plantations and mixed natural hardwoods dominate the landscape. Loblolly pine is widely grown in the Southeast for fiber and timber. Pine's site requirements and productivity are well documented. The pine industry has developed improved varieties with growth rates rivaling hardwoods at lower costs of production. Because of existing stands and know-how, the Southeastern forestry community considers loblolly to be a prime candidate for commercial bioenergy in the region. Biomass harvests of young pine plantations are additional potential components in an integrated pine-production system capable of generating multiple products, including energy, pulp, and solid-wood products, during the life of the stand. Extensive mature stands of natural mixed forests could also play an important role in future bioenergy feedstock supplies.

10. Recommendations

Independent tree farmers and the commercial forestry industry have developed valuable hardwood experiences that

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merit dissemination and offer insights into future research needs. Follow-on work is recommended to develop an efficient system to facilitate cooperation and information exchange among producers, researchers and government agencies. A first step could be to catalogue and provide access to relevant data on hardwood plantation productivity. Further research using consistent measures and data standards is required to verify estimated productivity levels across soil classifications, translate forestry soil groups into standard USDA soil maps, and map out the potential productivity for hardwoods in the Southeast. More investment in selection and breeding is needed for short-rotation plantation hardwoods to become more competitive as biofuel feedstock. Research is needed to systematically improve promising varieties, reduce demands for inputs (production costs), and develop more-efficient practices for managing hardwood plantations and natural forests. Conversion technologies and systems for adapting the plentiful biomass resources contained in southern pine and mixed hardwood forests to the needs of biofuel industries merit further research.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biombioe.2010.05.005.

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