Chapter 2

Woody Biomass from Short Rotation Energy Crops

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Short rotation woody crops (SRWCs) are ideal for woody biomass production and management systems because they are renewable energy feedstocks for biofuels, bioenergy, and bioproducts that can be strategically placed in the landscape to conserve soil and water, recycle nutrients, and sequester carbon. This chapter is a synthesis of the regional implications of producing four genera of short rotation energy crops as feedstocks for fuels, chemicals, and fibers set in the rich history of research and development of these purpose-grown trees in the United States. The four genera include: *Populus* (cottonwoods, poplars, aspens), *Salix* (willows), *Pinus* (southern pines), and *Eucalyptus* (eucalypts). Key aspects of the production systems are discussed, including tree biology, genetics and tree improvement, and silvicultural management. The availability

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of short rotation woody biomass is evaluated on the basis of maintaining sustainability at multiple scales. Current efforts to maximize production are described. Overall, sustainable production of fuels, chemicals, and fibers from woody biomass depends on a combination of feedstocks from both forests and plantations; the importance of dedicated SRWC feedstock production systems is highlighted.

Keywords: cottonwood; ecosystem services; energy security; eucalypts; hybrid aspen; intensive forestry; poplar; southern pine; sustainability; willow; woody feedstocks

General Introduction

Forest biomass constitutes ~30% of the total biomass that can be produced in the United States (U.S.), making adequate woody feedstock availability necessary for environmental and economic sustainability. Woody feedstock production is vital for achieving our National goal of 16 billion gallons of cellulosic ethanol by 2022 (*1*). Improved woody biomass production and management systems are needed to: maintain healthy forests and ecosystems, create high paying manufacturing jobs, and meet local/regional energy demands. Short rotation woody crops (SRWCs) are ideal for such systems because they are renewable energy feedstocks for biofuels, bioenergy, and bioproducts that can be strategically placed in the landscape to conserve soil and water, recycle nutrients, and sequester carbon (*2*). Also, these crops are ideal for genetic improvement because of their ease of propagation, relatively short generation time, and broad range of genetic variation. Such variability can, however, contribute to sub-optimal productivity if genotypes are not properly matched to conditions at specific sites of deployment (*3*). Sustainable production of fuels, chemicals, and fibers from woody biomass depends largely on understanding factors regulating genotype × environment interactions, in addition to components such as nutrient management, retention of biodiversity in the landscape, and proper weed and pest control.

The selection of species and the genetic improvement for use as a feedstock will have to take different approaches to serve the two biofuel platforms: 1) biochemical (sugar) and 2) thermochemical (pyrolysis). For the biochemical platform of fuel production trees have been seen by some as a less desirable feedstock because of their high lignin content and recalcitrance to digestion. However, trees with naturally low levels of lignin and high cellulose have been found, e.g. in the hybrid aspen clone 'Crandon' (*4*) and loblolly pine (*5*). Transgenic aspens have been produced with lignin levels reduced by over 50% (*6*). Furthermore, work conducted at the U.S. Forest Service, Forest Products Laboratory has found that native aspens (*Populus tremuloides* Michx. and/or *P. grandidentata* Michx., bulked feedstock) have very low recalcitrance and are particularly easy for enzymatic conversion to glucose (*7*). Recent studies have also shown that clone NE-222 (*P. deltoides* Bartr. ex Marsh × *P. nigra* L.) is much more conducive to enzymatic conversion relative to clone NM6 (*P. nigra*

× *P. suaveolens* Fischer subsp. *maximowiczii* A. Henry) (*8*). Moreover, wood biomass is the preferred feedstock for the pyrolytic production of bio-oils because high lignin, with its greater energy density, is a desired characteristic (*9*, *10*). "Lignin has less oxygen than carbohydrate (so there is less to remove) and higher energy density, meaning more energy content per ton of biomass processed" (*11*). Whether for fuels, chemicals, or fibers from woody biomass, it is necessary to understand the biology, genetics and tree improvement, and silvicultural management of candidate trees. Such factors are described below for four SRWC genera: *Populus* (cottonwoods, poplars, aspens), *Salix* (willows), *Pinus* (southern pines), and *Eucalyptus* (eucalypts) (Figure 1; Tables Ia−Ic.

Short Rotation Energy Crops

Populus

Introduction

It has been projected that *Populus* SRWCs could be grown as an energy crop on at least 24 million ha of U.S. land that currently supports marginal or environmentally-risky agriculture (*12*), which is nearly 450 times that currently deployed in North America (Table II). More SRWC research and practice has been conducted with the genus *Populus* than any other taxa. In fact, the genome of the Pacific Northwest cottonwood (*P. trichocarpa* Torr. & Gray) was the first of any woody species to be sequenced (*13*). Many excellent compendiums of *Populus* work are available (*14–16*). However, most of that research and essentially all of the practice has focused on the paper, and more recently, solid wood industries. It is clear that bioenergy could be a third product derived from the larger trees now being grown in *Populus* SRWC stands. *Populus* SRWCs are quite ready to fit into a multi-output biorefinery system (*17*, *18*). However, if *Populus* is to be optimally grown solely for conversion to bioenergy, it is likely that rotations shorter than five years, redesigned plantation structure, and the use of coppice regeneration will be necessary. Commercial coppice systems for *Populus* are only in the early stages of development. Obtaining woody biomass from these new systems is the primary subject of this review.

The eastern cottonwood (*P. deltoides*) has been the backbone of biomass production research in the North Central and Mississippi River Valley regions (Table Ia). *Populus deltoides* is found in nature from North Dakota to Texas to North Carolina, particularly along streams (*19*), but also in places where disturbance has greatly reduced other plant competitors and there is ample moisture for germination and early growth. In the northern U.S., *P. deltoides* has been the female parent for most of the development of hybrid planting stock (*20*, *21*). The European (*P. nigra*), Asian (*P. suaveolens* subsp. *maximowiczii*), or Pacific Northwest (*P. trichocarpa*) cottonwood have been used as the male parent to achieve faster early growth and better rooting. However, in the eastern U.S. from Madison, WI southward most of these interspecific hybrids are too susceptible to Septoria canker (*Septoria musiva* Peck) to be grown on rotations much over five years in length (*22*, *23*). Clones with pure *P. deltoides* backgrounds

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are much safer to use if they can be readily established from cuttings. *Populus deltoides* clones selected for good field rooting of dormant cuttings have been developed for use in the southern U.S. (*24*), but rooting of such genotypes has been erratic at northern latitudes (*25*). In other cases, rooted cuttings can be produced in standard tree nursery beds and then transplanted as rooted stock to field sites; the extra cost is more than offset under some environment conditions by higher survival and establishment growth (*26*, *27*).

Extensive native stands of quaking aspen (*P. tremuloides*) are only found in the northern part of the Lake States and the Rocky Mountains (*28*), while bigtooth aspen (*P. grandidentata*) is found in the Lake States and as scattered clumps from Iowa to North Carolina (*29*). Early settlers brought the European white poplar (*P. alba* L.) with them as a yard tree and it is now naturalized and/or hybridized with bigtooth aspens in additional small groves scattered across the same area.

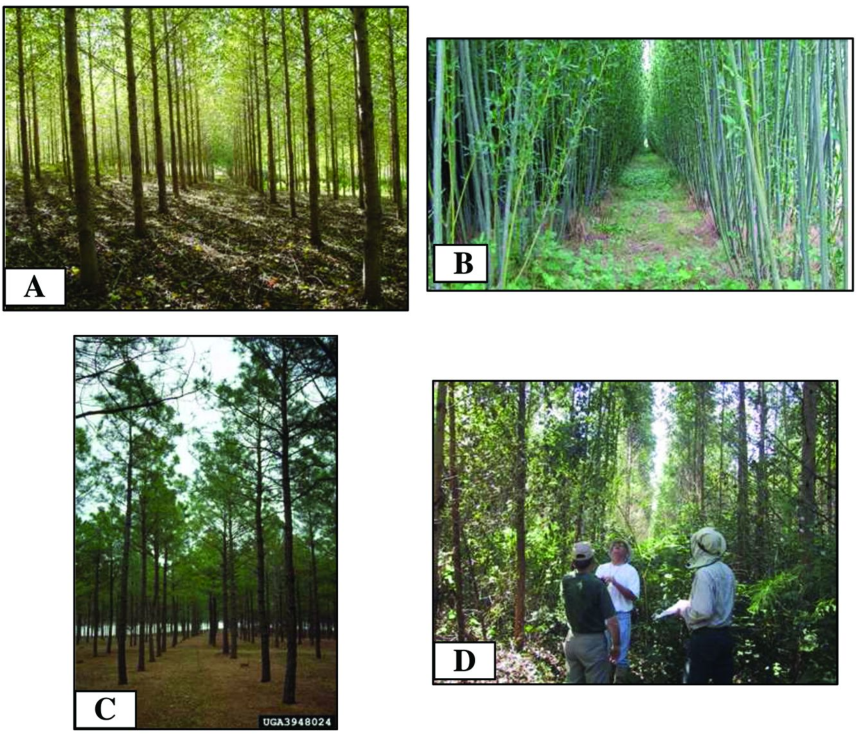

Figure 1. Plantations of Populus (A), Salix (B), Pinus (C), and Eucalyptus (D). Midrotation hybrid poplars in Minnesota (A; photo by Ron Zalesny, U.S. Forest Service); shrub willows in Upstate New York (B; photo by Tim Volk, State University of New York); loblolly pine after first thinning in Georgia (C; photo by University of Georgia –Bugwood); eucalypts on phosphate mined lands in Florida (D; photo by Don Rockwood, University of Florida). (see color insert)

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Table Ia. Species of potential short rotation energy crops that are most commonly used in different regions of the United States

			--------------- Populus ---------------				
Species	***Northeast***	***Lake States***	***Pacific Northwest***	***East Central***	***Midwest***	***Southeast***	***Southwest***
P. deltoides	Some	Some	In hybrids		Primary	Primary on alluvial sites	Experimental species and hybrids
P. nigra	In hybrids	In hybrids	In hybrids		Some in hybrids		Experimental as hybrids
P. suaveolens subsp. maximowiczii		In hybrids	Some in hybrids		Some in hybrids		
P. trichocarpa			Some and in hybrids				
P. alba		In Michigan	Some	Some in hybrids	Primary	Some in hybrids	Experimental as hybrids
P. grandidentata		Some in hybrids	Some in hybrids	Some in hybrids	Some in hybrids	Some in hybrids	Experimental as hybrids
P. tremula		Some in hybrids	Some in hybrids		Some in hybrids		

Table Ib. Species of potential short rotation energy crops that are most commonly used in different regions of the United States

--------------- *Salix* ---------------	
Species / Parentage	***Clone*** *(currently recommended for SRWCs in the northeastern United States)*
S. purpurea	Allegany, Fish Creek, Onondaga
S. sachalinensis × *S. miyabeana*	Canastota, Sherburne
S. purpurea × *S. miyabeana*	Millbrook, Oneida
S. viminalis × *miyabeana*	Otisco, Owasco, Tully Champion
Salix × *dasyclados*	SV1
S. sachalinensis	SX61
S. miyabeana	SX64
S. miyabeana	SX67
--------------- *Pinus* ---------------	
Special note: There are numerous families of *P. taeda* that are used according to site, latitude and longitude ranging from Virginia to eastern Oklahoma and Texas. Hybrids are not used.	

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Table Ic. Species of potential short rotation energy crops that are most commonly used in different regions of the United States

	---------------*Eucalyptus* ---------------	
Species	***Peninsular Florida / Hawaii***	***Lower Southeast***
E. grandis	Yes	No
E. amplifolia	No	Yes
E. benthamii	No	Yes
E. macathurii	No	Yes
Hybrids	Yes	No

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Table II. Description of industrial *Populus* plantations being grown in North America [adapted from Eaton (*76*)]

Region	*Land (ha)*	*Rotation (yrs)*	*Productivity (Mg ha^{-1} yr^{-1})*	*Primary use*
North Central	10,125	10 to 12	6.7 to 13.5	Pulp
Pacific Northwest	17,025	7 to 15	9.0 to 15.7	Solid Wood
Mississippi River Valley	11,350	8 to 10	4.5 to 6.7	Pulp
Canada	15,000	12 to 18	2.2 to 9.0	Pulp

Besides their potential use for biofuels, bioproducts, and bioenergy, the *Populus* species and hybrids have been extensively used for paper and particle board production with some work in making construction lumber (*30–32*). *Populus* genomic groups are also used in phytotechnologies to remove contaminants from soils and water (*33–35*). Utilizing wastewaters such as landfill leachate as irrigation and fertilization of *Populus* SRWCs may also contribute to the sustainability of growing the trees for energy-related applications (*36*, *37*).

Key aspects of *Populus* SRWCs are summarized here, including tree biology, genetics and tree improvement, and silviculture. Current efforts to maximize bioenergy production of cottonwoods, poplars, and aspens are described, and the opportunities afforded by *Populus* SRWCs are highlighted.

Biology

In North America, cottonwoods, poplars, and aspens occupy large distributional ranges with abundant genetic variation (*38*). Such genetic diversity is a hallmark of *Populus*, with variation present at the genus, sectional, species, and clonal level (*39–41*). There are 29 recognized species of *Populus* worldwide (*40*, *42*), with twelve species native to North America. Species of *Populus* are outcrossers with dioecious trees bearing either male or female pendant catkins (*38*, *40*, *43*). The ratio of male to female trees is generally 1:1, but variations exist at low altitudes with pistillate dominance and high altitudes with staminate dominance (*38*, *44*, *45*). The fast growing, deciduous, single-trunked trees are most notably researched and utilized for intensive management due to ease of rooting and vegetative propagation, quick establishment and fast growth leading to elevated rates of photosynthesis and transpiration, and the ability for some species to resprout (e.g., coppice) following harvesting or other top-killing events. Consequently, these three features make *Populus* genotypes particularly suitable for biomasss production, as well.

First, ease of rooting and vegetative propagation are key traits of the cottonwoods, particularly *P. nigra*, *P. trichocarpa*, and *P. suaveolens* subsp. *maximowiczii*. Tree breeders, silviculturists, and horticulturists take advantage of the propensity for these species to form adventitious roots by using unrooted hardwood stem cuttings as a common and inexpensive propagule in managed

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systems (*25*). Short stem pieces, about 30 cm long from one-year-old dormant material, quickly form shoots from dormant buds and roots from root primordia distributed throughout the stem (*27*, *42*, *46*, *47*). Additionally, adventitious roots form from callus, a wound-induced parenchymous growth at the base of the cutting. Riparian cottonwoods (i.e., *P. deltoides*) naturally reproduce asexually by branch breakage and crown damage. Branch sprouting and adventitious root formation facilitate tree survival (*43*). While some genotypes root well from unrooted cuttings, one of the chief drawbacks with *P. deltoides* is that rooting from unrooted, dormant hardwood cuttings is often erratic. In addition, a type of planting stock that is commonly used for *P. deltoides* is rooted cuttings with multiple lateral roots and some residual stems (usually not greater than one meter in height), or rooted cuttings reared in a greenhouse or growth chamber (see above).

Second, the leaves have a flattened, or otherwise flexible, petiole that gives them their characteristic quaking or fluttering appreance with the slightest of breezes. It has been postulated and to some extent proven that this helps the trees maximize photosynthetic rates across layers of leaves that would otherwise be shaded. Whatever the mechanisms, the *Populus* trees are usually the fastest growing components of temperate deciduous forests (Figure 1).

Third, in the cottonwoods, the ability to resprout is confined primarily to the stumps and it diminishes with age and frequent coppicing (*27*, *48*). In one of the few studies of repeated coppicing, cottonwoods planted on 0.6 × 1.2-m or 1.2 × 1.2-m spacings and cut on two-year cycles had high sprout vigor after the first cut, diminishing vigor after each of the next two cuts, and substantial mortality and loss of vigor beyond that (*48*). In most aspens, all or most of the sprouting comes from the roots, with root suckering following disturbance being much more important than seedling establishment. The sprouting potential is present in one-year-old seedlings, but tends to increase with age until the trees decline in vigor (*28*, *29*, *49*). The European white poplar sprouts well from the stump at young age as well as producing good root sprouts (*50*).

Genetics and Tree Improvement

The genus *Populus* is divided into six sections, based on specific ecological and morphological traits: *Abaso*, *Turanga*, *Leucoides*, *Aigeiros*, *Tacamahaca*, and *Populus* (*40*). The most important species for short rotation culture are in the sections *Aigeiros*, *Tacamahaca*, and *Populus*. Major barriers to hybridization occur among sections, with the success of artificial hybridization ranging from complete compatibility to complete incompatibility (*41*). Intersectional hybrids of economic significance occur between *Aigeiros* and *Tacamahaca* (*51–54*), with greater success being obtained when species of *Aigeiros* are used as females with *Tacamahaca* males (*51*, *52*, *55*). In addition, hybrids are common within and among species of the sections *Populus*; however, hybrids between this section and others are difficult to obtain (*56*, *57*).

The genus *Populus* was one of the first to undergo genetic improvement to meet human use goals (*14*). Poplar breeding was started in the U.S. in 1934

(*20*). In the 1990s there were active breeding and/or selection programs for the *Aigeiros* and *Tacamahaca* sections in at least 21 states and 4 Canadian provinces. Unfortunately, only two active breeding programs remain in the U.S. As interest in biomass production grows, some programs may be restarted and new ones begun, but valuable time and often important germplasm has been lost. A summary of traits important to SRWCs of bioenergy has been developed (i.e., ideotype) (*16*). In particular, emphasis will need to be placed on ease of rooting of dormant cuttings and the retention of stump sprouting vigor over several rotations. It is possible that *P. nigra*, *P. suaveolens* subsp. *maximowiczii*, and *P. trichocarpa* can contribute to sprouting ability, just as they have to improved rooting. In current uses of SRWC *Populus*, it is assumed that enough genetic improvement progress is made over the course of a rotation to warrant replacement with new clones after each harvest. New guidelines will likely be needed for shorter rotations focused on bioenergy.

Selection for biomass yield has usually focused on approximate stem volume using some form of a D^2H formula, often times with an initial selection based on height and then for diameter. That priority order was reversed in the improvement program at Iowa State University based on the hypothesis that the shade avoidance response of pioneer species like those within the genus *Populus* naturally selects for height growth at the expense of growth allocated to diameter (*58*, *59*). A significant amount of the improvement in corn (*Zea mays* L.) yield was achieved by breeding out the shade avoidance (i.e., interplant competition) response (*60*). The concept still needs rigorous scientific testing, but the empirical results were good (*22*). However, there was one drawback, a small but significant negative correlation was found between diameter growth and specific gravity. It is theorized that selecting for faster growth tended to select for more vessel area to support higher levels of photosynthesis and rapid supply of soil nutrients to developing tissues. Selecting for optimal allocation of biomass will be even more important with frequent coppicing. One of the biggest benefits in this area will be increased understanding of the biology of wood formation and the ability to either down- or up-regulate the production of constituents like lignin to fit the needs of a particular conversion technology (*61*).

The cottonwoods are subject to some serious pest problems. For about the first three years of plantation development the cottonwood leaf beetle (CLB) (*Chrysomela scripta* Fabricius) can cause over 50% growth losses and deform stem growth (*62*). No significant genetic resistance has been found in *P. deltoides* clones and most hybrids. Fortunately, the insect can be controlled with careful crop scouting and spraying with an appropriate Bt formulation as each generation begins to emerge (*63*). Since bioenergy rotations may be entirely or mostly within the three-year period of high susceptibility, a renewed focus on developing transgenic insect resistance in *Populus* may be necessary (*64*).

A major leaf disease, poplar leaf rust (*Melampsora medusa* Thümen), can reduce cottonwood growth by 40%. Breeding and selection for resistance is possible and a single dominant resistance allele has been identified (*65*). As indicated earlier, the most serious disease of cottonwood-type hybrids in the eastern U.S. is Septoria canker. Hybrids with *P. trichocarpa* succumb to the disease after just a few years. *Populus nigra* and *P. suaveolens* subsp. *maximowiczii* hybrids may survive long enough for use in bioenergy rotations of

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five years or less (*66*). Pure *P. deltoides* clones are usually resistant to Septoria canker disease.

Moreover, an extensive program on aspen genetics and improvement was started by the Institute of Pulp and Paper Chemistry in Appleton, WI and later transferred as the Aspen and Larch Cooperative to Grand Rapids, MN. Significant progress was made on stem biomass production with the native aspens. In particular, the selection in the wild and the production through breeding of triploid aspens gave simultaneous and substantial increases in growth rate, fiber length and specific gravity (*67*). Polypoidy can also be induced through colchicine treatment and tissue culture techniques (*68*). A return to polyploidy research would likely give rapid and significant results in the improvement of biomass production. A program of interspecific hybridization with *P. alba* was initiated by the Appleton group with promising early results. However, a new disease called bronze leaf [*Apioplagiostoma populi* (E.K. Cash & Waterman) M.E. Barr] began to be seen in the hybrid clones (*69*, *70*) and the hybrid work was curtailed in Wisconsin and Minnesota; some improvement work with the native aspens continues.

Nature started its own interspecific breeding program in places where *P. alba* had been introduced into the vicinity of the bigtooth aspen. In the 1940s and 1950s several distinctive hybrid clones were discovered in southeastern Iowa (*71*). The most notable genotype is the 'Crandon' clone that has shown superior growth rates over a very wide geographic area from southern Minnesota to northern Alabama and east to West Virginia ((*3*, *72*); unpublished industry plantation results). Bronze leaf disease has not yet become a problem in Iowa and areas to the south and east. With the success of the Crandon hybrid aspen and the apparent absence of most insect and disease problems a modest breeding program was first conducted in 1990 to 1991 by Patrick McGovern, a private breeder in Michigan using a variety of *P. alba, P. grandidentata, P. tremula,* and F_1 hybrid parents. Progeny tests were established in Iowa and other nearby states under the U.S. Department of Energy's Biofuels Development Program. Clonal selections were made from one of those trials and a clone test was established in 1996 (*73*) and harvested in 2008. Three of the top five clones in biomass production were pure *P. alba* selections, one was a *P. alba* × *P. tremula* hybrid and the other was a *P. alba* × *P. grandidentata* hybrid. Eleven of the new clones outperformed the Crandon clone. Specific gravity ranged from 0.28 to 0.43 g cm^{-3}. The two best stump sprouters were sibling clones from the *P. alba* × *P. grandidentata* cross. One *P. alba* family was produced with a heterozygous fastigiate male parent (Bolleana cv.). The best biomass producer of the family was a fastigiate clone that ranked seventh overall. However, the other fastigiate clones were poor biomass producers, as were the two normally branched clones (*74*).

Silviculture

Standard practices in traditional *Populus* SRWCs are well detailed in previous reviews (*27*) and are similar for energy plantations (especially for site preparation and vegetation management). Essentially all commercial cottonwood type SRWC plantations are established with unrooted cuttings from 15 cm (north) to 45 cm

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(south) long. To start aspen plantations, rooted plants can be produced in the nursery from segments 10 cm long and about 0.5 to 2 cm thick (*75*). A new method of rooting 10 cm long by $\leq$ 0.5 cm diameter dormant stem cuttings is under development.

Most cottonwood and aspen plantations have been planted on something close to a 3 × 3 m spacing with intensive weed control for one to three years, and harvest at 7 to 15 years (18 years in Canada) (Table II) (*76*). Yields for cottonwood and hybrid poplar stands range from 2.2 to 15.7 Mg ha^{-1} yr^{-1} on these rotations (Table II) (*3*, *27*). In contrast, a series of Crandon hybrid aspen yield trials in Iowa resulted in an average of 25 Mg ha^{-1} yr^{-1} on a 10-year rotation (*72*). However, to really maximize SRWC yields for bioenergy, much more work needs to be done in optimizing spacing and harvest age. For example, a Nelder spacing design was used with the Crandon hybrid aspen clone to determine the age:spacing:yield relationships for the first rotation (*77*), and a similar approach was used to study cottonwood yields as a function of spacing and number of coppice rotations (*48*). A limited amount of work has been done with *Populus* in testing the double row system of planting cuttings that has been used so successfully with willows (see below) (*78–80*) and more is needed on this and other innovative planting designs.

Extensive research has been done on managing root sprouts in native aspen stands (*49*). Unfortunately, research on SRWC root sprouts has only just begun (*81*). First year re-sprouting can result in over 200,000 stems ha^{-1} from a combination of stump and root sprouts with natural thinning starting during the first year. When the original plantations are harvested, a combination of both stump sprouts and root sprouts is produced. Observations of such mixed sprout origins suggest that stump sprouts have the fastest growth over the first one to two years, leading to significant mortality in adjacent root sprouts. After about two years, the stump sprouts begin to decline in health, vertical stability, and survival relative to the remaining root sprouts. Our results to date indicate that the yield per unit area harvested in a thinning at the end of the first year could be as much as 5.5 Mg ha^{-1} (root sprouts 3.3 Mg ha^{-1}, stump sprouts 2.2 Mg ha^{-1}) with no new establishment costs.

A new agroforestry study was initiated in 2009 by planting Crandon trees at a 3.0 × 3.6 m spacing into a matrix of forage triticale (*Triticale hexaploide* Lart.) established the previous fall. The triticale is harvested as a biomass crop in June leaving stubble for soil protection and making more soil water available to the trees. The triticale left unharvested next to the trees dies by early July, but remains standing for most of the rest of the season. Triticale biomass cropping between the tree rows can be repeated over the first few years until the trees dominate the site and go on to complete an 8- to 10-yr initial rotation. Alternatively, aspen root spread is being monitored so we can determine if a first-rotation stand can be converted to coppice production cycles after a only few years of harvesting triticale as the main biofuels feedstock. Lateral root spread of up to 2.4 m distal from stems was documented in the first year (*82*).

Not enough attention has been given to clonal deployment strategies with the genus *Populus* (*83*). The recommended deployment of willow clones from different diversity groups across the landscape is discussed below. The standard approach to *Populus* plantations has been to plant a mixture of monoclonal

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blocks, with each block being many hectares in size. Essentially all cottonwood type clones are planted this way, often wihout attention to diversity among adjacent clones. Deployment strategies for aspen plantations should also be further evaluated. The aspens may be more tolerant of interclonal competition and within block mixtures may provide a way to reduce the costs of both time and money during clonal testing (*84*). A mix of proven and promising clones can be established in commercial plantations. The best clones for each particular site will crowd out the less suited clones. When the first rotation stands are harvested, the majority of the sprouting should be from the most vigorous clones under the local environmental conditions and these naturally selected clones should continue to dominate in successive coppice rotations.

Salix

Introduction

Shrub willow (*Salix* spp) has been developed as a perennial energy crop for the production of biomass in North America and Europe during the past 40 years (*37*, *85–87*). Willow research in North America started in southeastern Canada at the University of Toronto (*88*) and in Upstate New York in the mid 1980s (*86*). Currently, yield trials have been carried out or are under way in 15 states in the U.S. and in six provinces in Canada (Figure 1). Commercial nurseries have been developed to supply willow planting stock and over 400 ha of commercial scale plantings have been established in the U.S.

In addition to yield studies of different willow clones across sites, research in North America focused on various components of the production cycle, including nutrient amendments and cycling, alternative tillage practices, incorporating cover crops into these systems, density studies, harvesting systems development, and assessing pest impacts. A range of environmental characteristics of willow biomass crops have been assessed as well, including use of willow plantations by birds, changes in soil micro arthropod communities under willow, changes in soil carbon, and life cycle assessments of the system. The economics of the production system have been assessed and a cash flow model to reflect current production methods has been recently developed (*89*). In addition, breeding and selection programs for shrub willows have been developed in Canada and the U.S. The Canadian program was terminated in the early 1990s and the U.S. program that started in 1995 is still producing improved clones of willow for both the biomass production and agroforestry markets (*90*).

Key aspects of *Salix* SRWCs are summarized here, including tree biology, genetics and tree improvement, and silviculture. Current efforts to maximize production of willows are described, and the opportunities afforded by *Salix* SRWCs are highlighted.

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Biology

Species from the genus *Salix* are perennial, deciduous, shade intolerant pioneer species that are typically found primarily on moist soils along water ways in natural settings. Although willows inherently have a competitive advantage over other plants in wet conditions, they grow well on uplands and well-drained sites as long as competing vegetation is controlled during establishment and there is adequate rainfall (*91*). Willows are dioecious plants that produce catkins during the spring, typically before the leaves come out. The seeds contain silky white hairs, which allow them to be dispersed by wind, but they are typically only viable for a few weeks and require moist conditions to germinate and develop (*92*). Most willows are native to the temperate, boreal, and tundra regions of the northern hemisphere (*93*), with shrub willows being used for bioenergy crops coming primarily from temperate regions. Shrub willows have the ability to be propagated vegetatively and regrow after coppicing, which facilitates rapid multiplication and allows repeated harvests from a single planting.

Although weed competition and drought are the greatest threats to the establishment of a willow plantation, diseases and pests have the ability to impact the productivity of a crop. The fungus *Melampsora epitea* Thüm, which causes rust disease, has reduced yields in the United Kingdom and is being monitored in the U.S. It attacks leaves, causing them to senesce and drop prematurely. Rust is a concern for *S. eriocephala* Michx., but has limited impact on species and hybrids being used for biomass production in North America right now. Diseases that have less impact include anthracnose tip blight on *S. eriocephala* caused by *Colletotrichum* spp. and willow scab caused by *Physalospora miyabeana* Fukushi (*94*). Pests and insects documented in North America include Chrysomelid beetles, which include *Popollia japonica* Newman (Japanese beetle) and *Plagiodera versicolora* Laicharting (imported willow leaf beetle) in the U.S. (*95*). These beetles feed on the leaves of the willow and in the U.K. have been shown to decrease yields of susceptible willow clones (*96*, *97*). Stem-sucking insects such as *Tuberolachnus salignus* Gmelin (giant willow aphid) and *Pterocomma salicis* L. (black willow aphid) have been documented in shrub willows as well (*98*). To date none of these pests have had a measureable impact on yields of willow biomass crops in North America, but with increasing acreage, pest and disease pressures could create serious problems (*94*).

Genetics and Tree Improvement

Large genetic diversity and limited domestication of willow to date provide great opportunities to improve yield and other characteristics. The genus *Salix* comprises between 330 and 500 species (*93*, *99*, *100*) growing as trees, shrubs and dwarf shrubs. Polyploidy is common and some species are known to hybridize within the genus *Salix*. The species used for woody crop systems are primarily from the subgenus *Caprisalix* (Vetrix), which has over 125 species (*92*). These species share many characteristics, but differ in their resistance to pests and diseases and their architecture. Breeding and selection can improve yields across a wide range of site conditions, identify clones that are tolerant to diseases and pests, and identify growth forms that are more suitable for harvesting systems used for SRWC. Once superior willow clones are identified they can be multiplied rapidly using vegetative propagation.

Willow breeding started in Sweden and the U.K. in the 1980s and early 1990s, but many of the European clones did not perform well in North America due to damage caused by the potato leaf hopper (*Empoasca fabae* Harris). Willow breeding in North America started at the University of Toronto (UofT) in the 1980s and focused on heritability and genetic variation of native species such as *S. eriocephala*, *S. exigua* Nuttall., *S. lucida* Mühl., *S. amygdaloides* Anders., *S. bebbiana* Sarg., *S. pellita* Anders., *S. petiolaris* Smith, and *S. discolor* Mühl. Early studies with *S. eriocephala* showed that limited gains would be possible when breeding and selecting for height, diameter and yield (*101*, *102*). Breeding started in 1998 at SUNY-ESF with a variety of species including *S. eriocephala*, *S. sachalinensis* F. Schmidt, *S. purpurea* L., or *S. dasyclados* Wimm. with *S. miyabeana* Seemen and intraspecific crosses of *S. purpurea*. In four plant plot selection trials the highest yielding improved clone produced 77% more biomass than the reference clone 'SV1' (*S. dasyclados*) in the second rotation (*94*). First rotation yields of improved clones in small plot yield trials have been greater than reference clones and have ranged from 10.2 to 13.6 Mg ha^{-1} yr^{-1}. Previous studies indicate that there are different strategies for obtaining high biomass production among groups of willow species and clones (Table III) (*103*). These results indicate that there is a large potential to make use of the wide genetic diversity of shrub willows to improve yields with traditional breeding and selection.

Improving yields will make willow a more economically attractive crop for marginal lands. Increasing yields by 17% (from 12 to 14 Mg ha^{-1} yr^{-1}) improves the internal rate of return (IRR) for willow biomass crops by 51% (from 5.5 to 8.3%) (*89*). First-year rotations of willow have produced yields of 8.4 to 11.6 Mg ha^{-1} yr^{-1} (*86*, *104*, *105*) and second-year rotations yields are about 35% higher on average (*106*).

Silviculture

Willow can be grown on marginal agricultural lands in temperate regions. It should be planted in fully prepared open land, where weeds have been controlled. Typically field preparation starts the fall of the year before planting and includes a combination of mechanical and chemical techniques. Planting takes place in the spring between the end of April and the beginning of June. Erosion during establishment year has been successfully reduced through the use of cover crops, such as *Secale cereale* L. (winter rye) (*107*). Studies to evaluate conventional tillage, no tillage and conservation tillage methods are under way as well.

Table III. Differences in morphological traits of *Salix* clones with high biomass production in short rotation woody crop systems [adapted from Tharakan et al. (*103*)]

Species group (variety name)	*Mean stem diameter (cm)*	*Number of stems per stool*	*Wood specific gravity (g cm^{-3})*	*Leaf area index*	*Specific leaf area (cm^2 g^{-1})*	*Foliar N (g kg^{-1})*
S. purpurea, *S. dasyclados* (SV1)	1.2	10.7	0.43	3.9	125.6	20.7
S. sachalinensis (SX61), *S. miyabeana* (SX64, SX67)	1.6	5.9	0.39	4.5	129.7	14.7

Willows are planted as unrooted dormant hardwood cuttings using tractor drawn planters. The early planters were adapted from potato planters to plant 20 to 25 cm cuttings. Currently available planters from Sweden (Step Planter) and Denmark (Egedal Energy Planter) use 2 to 3 m whips and cuts them into 15 to 20 cm long sections and inserts them into the ground. Shrub willows are typically planted in a double row system at 15,000 plants ha^{-1}, with 1.5 m between the double rows, 0.76 m within the double-row and 0.61 m between the plants within the rows, to allow clearance for harvesting and cultivation machinery. Trials are underway to examine the potential of reducing planting density of new clones to decrease establishment costs while maintaining yields. Single (*108*) and triple row systems have also been used in some plantings. After the first year the willows are cut at about 5 cm above the soil after leaf drop. This process is called coppicing and increases the number of stems from 1 to 3 up to 8 to 13 depending on the clone (*103*). Coppicing facilitates future harvests, increases yields and helps to control weed competition due to earlier canopy closure.

Typically willows are harvested every 3 to 4 years using forage harvesters with a specially designed cutting head (*109*). Whole stem harvesters and modified bailers have also been developed. Following harvest the plants will re-sprout the following spring when they are typically fertilized with about 100 kg nitrogen (N) ha^{-1} of commercial fertilizer or organic sources like manure or biosolids (*109*). Projections indicate that the crop can be maintained for seven rotations before the rows of willow stools begin to expand to the point that they are no longer accessible with harvesting equipment.

Pinus

Introduction

Southern pine species are an important component of the forest resources of the U.S. South, which is one of the most important timber producing regions globally (*110*). Of the over 74 million ha total timberland in 11 southern states (excludes Oklahoma and Kentucky), 27.5 million ha are classified as softwood types and another 8.5 million ha are oak-pine types (*111*). Pine plantations account for 15 million ha, more than half of the area of softwood forest. The intensification of pine plantation silviculture is one of the remarkable stories of U.S. forestry (*112*) and it sets the stage for discussing the potential role that short-rotation pine could play in woody bioenergy development.

The historical development of intensive pine forestry has been described as a process of crop domestication (*112*, *113*). Several authors have described this process from multiple perspectives (*112–116*). In broad outline, intensification has involved tree improvement, seedling quality and stocking control, site preparation, management of competing vegetation, fertilization, and pest management (*114*, *116–118*). Research on soil-site and growth and yield have ensured that the potential gain in productivity from these basic improvements is realized by properly deploying improved planting stock and appropriate silvicultural interventions (*112*). More than 95 percent of the seedlings planted in the South are genetically improved loblolly and slash pines (*Pinus taeda* L. and *P. elliottii* Engl., respectively) (*118*).

The distinguishing feature of timberland in the South is that private ownership predominates. Fully 87% of all timberlands in the South and 95% of the pine plantations were privately owned in 2007 (*111*). These numbers obscure structural shifts in ownership that have already occurred and shifts in timberland location projected to occur in the near term (*119*). The nearly 20% of timberland formerly held by vertically integrated forest products companies (industrial land) is now largely owned by real estate investment trusts (REIT), timber investment and management organizations (TIMO), pension funds, and other financial institutions (*120*, *121*). Although non-industrial private landowners own a small percentage of the pine plantations, they account for a substantial area. The demographics of these owners suggest that this land area will soon see further ownership fragmentation through sales and generational transfers (*120*, *122*). Not all plantations will be managed at the same intensity so differing landowner objectives will affect whether biomass production for bioenergy is feasible and if so, which silvicultural system is adopted.

Rising population and increasing per capita wealth in the South will likely drive changes in land use (*119*). This combination of factors suggests that the center of intensive pine silviculture will shift westward as urbanization proceeds on the coastal plain and in the Piedmont (*121*). Indeed, Zhang and Polyakov (*111*) suggest that by 2027, plantation area will decline in Florida, Georgia, North and South Carolina by 3.5% and increase in Alabama, Mississippi, Arkansas, and Louisiana by 30%. While federal and state policy and market forces will determine where and how much land will be available for developing pine bioenergy plantations, these projected shifts into relatively drier areas will affect how accurately we can predict potential yield from currently available genetic material and silvicultural prescriptions. Possibilities for bioenergy production are several (*12*), including continued use of harvesting residues from traditional operations (see Skog et al. of this volume; (*123*)), possibly including more complete removal from sites; integrating bioenergy with production of other products; and developing dedicated bioenergy plantations on marginal agricultural land or cutover forestland. In all cases, current intensive management systems will continue to be developed.

A recent report from the U.S. Departments of Agriculture and Energy provides the best national estimate of how much biomass could be available for energy production from cropland and forests (*12*). They projected that approximately 342 million dry tons of biomass annually could come from converting from 16 to 24 million ha of agricultural land to perennial crops. This would add an additional 2.4 to 5.8 quadrillion BTUs of renewable energy (as compared to the 2.9 quads that came from biomass in 2003, which accounted for almost 3% of total energy consumption in the U.S. in that year).

Key aspects of *Pinus* SRWCs are summarized here, including tree biology, genetics and tree improvement, and silviculture. Current efforts to maximize production of southern pines are described, and the opportunities afforded by *Pinus* SRWCs are highlighted.

Biology

Of the four most common southern pine species, shortleaf pine (*P. echinata* Mill.) is the most widespread but it is not planted and little has been done to develop improved material, which probably disqualifies it from consideration for SRWCs. Slash pine (*P. elliottii*) was the backbone of the naval stores industry but its susceptibility to rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. fusiforme (Cumm.) Burds. & Snow) generally has limited planting to Florida and south Georgia. Since this is the area projected to lose plantation area due to land use change (*111*, *121*), slash pine also is an unlikely candidate for widespread SRWC planting. Longleaf pine (*P. palustris* Mill.) was once the most widespread of the southern pines and restoration of longleaf is a popular topic. Nevertheless, longleaf exhibits slow early growth; although the establishment problems once experienced with longleaf have largely been overcome, the growth habit of initially allocating most growth to belowground biomass limits its utility for short rotation plantings.

The rapid early growth and responsiveness to amendments of loblolly pine (*P. taeda*) has made it the pine of choice for intensive silviculture in the South (*124–127*) (Figure 1; Table Ib, and Table IV). The response to fertilization may depend on whether significant competition from shrubs or hardwoods is controlled (*116*, *126*), and interactions among site and genetics have been shown (*128*, *129*). Because there is much installed capacity and knowledge of loblolly pine intensive silviculture (*112*, *113*, *116*, *129*), it is the most likely prospect for bioenergy development. One drawback relative to hardwood species, however, is that loblolly pine does not coppice.

Fast-growing, densely planted SRWC pine plantations will be challenged by endemic organisms, including Nantucket pine tip moth (*Rhyacionia frustrana* Comstock), fusiform rust, and southern pine beetle (*Dendroctonus frontalis* Zimmerman). Tip moth affects rapidly growing material (*130–132*) and can result in sustained growth loss (*133*, *134*). Control of competing vegetation and

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use of insecticides that reduce levels of natural enemies may result in damage from insects that otherwise do not reach economically damaging levels (*131*). Fusiform rust has co-evolved with southern pines and will continue to challenge tree breeders to develop rust resistant planting stock. Mortality from fusiform rust is highest on young trees, and treatments to increase growth such as fertilization increases rust incidence. Thus, resistance to fusiform rust will be of prime concern in establishing SRWC pine plantations and recent advances in understanding the fusiform rust-loblolly pine pathosystem promise better strategies for avoiding losses (*135*). Southern pine beetle, another endemic disease, should present less of a problem in SRWC pine plantations as it more typically attacks larger, older trees. If there is an outbreak in the vicinity, however, even young pine stands can be decimated.

Genetics and Tree Improvement

Most of the loblolly pine seedlings planted in the U.S. are of genetically improved stock (*118*, *129*). As of 2002, 59% of all loblolly pine plantations were established as single, open-pollinated family blocks; on industry lands this was 80% (*129*). As material from advanced breeding programs becomes available for operational planting, most large organizations deploy this material to their best sites. In 2002, companies reported less than 1% of their material was planted as full-sib families (*118*). Individual clones from rooted cuttings or tissue culture have been planted in experimental plots and early results indicate that genotype × environment interactions are relatively unimportant under current conditions (*129*).

Biotechnology promises further advances in domesticating loblolly pine. Opportunities exist to enhance growth rates and reduce rotation (harvesting) ages, convey greater pest and disease resistance, and to produce trees with chemical and structural characteristics optimized for chemical processing (i.e., designer trees), as well as accelerating traditional breeding programs (*136*). Biotechnology may be used to genetically engineer these and other traits, but will require parallel efforts to overcome public misperceptions about the technology as transgenic trees become available for operational deployment.

Silviculture

Intensive pine silviculture in the South includes a variety of site preparation treatments appropriate to conditions, weed control, fertilization, and several thinnings during a typical 25-year rotation (Table IV). Before mergers and land divestitures in the 1990s (*112*, *120*), some forest industry companies concentrated on producing pulpwood-size material and experimented with shorter rotations that eschewed thinning and included tip moth control, obtaining peak annual growth increment of 3.1 to 3.6 Mg ha^{-1} yr^{-1} at ages 10 to 12 on some sites (*112*, *114*). Mean annual increment of 2.1 to 2.7 Mg ha^{-1} yr^{-1} was routinely obtainable on most sites (*127*, *137*).

Table IV. Silvicultural prescriptions and potential yields from intensively-managed *Pinus* plantations in the southern United States

Age (yrs)	*Sawlog*[a]	*Pulpwood*[b]	*Comment*
0	Site preparation	Site preparation	Aerially applied chemical, followed by combination plow[c]
1	Plant	Plant	Improved 1-0 bareroot seedlings; Flexwood system plants two levels of improved seedlings
1	Herbaceous weed control	Herbaceous weed control	Product and rate depend on site
2	Fertilize	Fertilize	Diammonium phosphate (DAP), 225 kg ha^{-1}
1 to 3	Tip moth control	Tip moth control	As needed[d]
5	Fertilize	----------	135 kg N ha^{-1}; 17 kg P ha^{-1},[e]
6	----------	Fertilize	135 kg N ha^{-1}; 17 kg P ha^{-1}
9	Fertilize	----------	135 kg N ha^{-1}; 17 kg P ha^{-1}
10	----------	Fertilize	135 kg N ha^{-1}; 17 kg P ha^{-1}
13	Thin and fertilize	----------	135 kg N ha^{-1}; 17 kg P ha^{-1}
14	----------	Harvest	138 to 152 Mg ha^{-1} (pulpwood[f])
17	Fertilize	----------	135 kg N ha^{-1}; 17 kg P ha^{-1}
19	Thin	----------	
21	Fertilize	----------	135 kg N ha^{-1}; 17 kg P ha^{-1}
25	Harvest	----------	134 to 157 Mg ha^{-1} (pulpwood/ energywood[g])

[a] Modeled silvicultural prescription from Allen et al. (*114*) [b] Modeled silvicultural prescription from Borders and Bailey (*127*); fertilizer rates are taken from Allen et al. (*114*) [c] Combination plow, usually pulled by a tractor with a V-blade to clear slash on cutover sites; plow combines coulter wheel and subsoiler followed by two bedding disks [d] Tip moth control is not generally operational but has been shown to provide an economically significant response in intensively-managed plantations (*112*). [e] On some loamy and sandy sites, studies have shown response to potassium and boron; some companies include complete micronutrient application where response is suspected. [f] Range is the average and optimistic level in Borders and Bailey (*127*). [g] Range is the medium and high level in Allen et al. (*114*); total yield was 228 Mg ha^{-1} with 157 Mg ha^{-1} pulpwood/energywood at the medium level and 309 Mg ha^{-1} total yield with 228 Mg ha^{-1} pulpwood/energywood at the high level.

There is little published information on loblolly pine SRWC but the information from studies comparing species and genotypes in dense plantings is illustrative, with loblolly generally out-performing slash and with a strong interactive effect of density and genotype for loblolly pine. Burkes et al. (*125*) compared four planting densities (740, 2220, 3700, and 4400 trees ha^{-1}) and found no significant difference in stemwood production after 4 years between the two denser spacings. Stem biomass growth in the fourth growing season was 17.4 Mg ha^{-1}. Adegbidi et al. (*138*) reported biomass accumulation and partitioning in four intensively managed loblolly pine stands planted at 1495 trees ha^{-1} with the same improved family. Stemwood growth after four years was 10.1 Mg ha^{-1} yr^{-1}, which accounted for 34% of net primary production. Roth et al. (*128*) obtained total aboveground biomass after five years from intensive treatments of 55 Mg ha^{-1} with 2990 trees ha^{-1} as compared to 37 Mg ha^{-1} for operational management at the same planting density. Varying the planting density also had an effect; under the intensive treatment, average stem diameter was 13.1 vs. 10.9 cm for 1334 and 2990 trees ha^{-1}, respectively (*128*). Most significantly, they identified the need for nutrient amendments on poor sites earlier in the rotation than is typical of conventional intensive silviculture.

Modifications to integrate bioenergy into current intensive pine silviculture have been proposed, including dual-cropping and intercropping. In dual-cropping, the pine stand is established and managed to intentionally produce both biomass for energy and crop trees for roundwood products (*139*). Direct-seeding pine between the rows of a traditional pine plantation produced about 10.2 Mg ha^{-1} of biomass for energy after 5 years without adversely affecting the crop trees (*139*). Another version of dual-cropping called FlexStand involves planting two pine genotypes together, a very elite genotype for the crop tree and an improved genotype for biomass (*140*). The advantage is that the lower value biomass is also a lower cost seedling. In the intercropping system, an annual bioenergy crop such as switchgrass is planted between the rows of the pine crop trees (*141*). The full details of spacing, harvesting, and the economics of these systems are being studied.

Eucalyptus

Introduction

Bioenergy could be the highest contributor to global renewable energy in the short to medium term, with SRWC *Eucalyptus* playing a major role (*142*). *Eucalyptus* species can be widely planted to produce abundant biomass, but their planting may require various incentives. Several biomass conversion technologies are operational, and other biomass opportunities include biorefineries, carbon sequestration, and small, distributed energy systems. Brazilian experience suggests that *Eucalyptus* bioenergy can be produced efficiently and sustainably in the U.S. (*143*). Biomass-derived electricity and liquid fuels may compete with fossil fuels in the short-term, most likely by using integrated gasifier/gas turbines to convert biomass to electricity (*144*).

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Bioenergy currently constitutes ~2.8% of the U.S. energy production, with ~60% of this due to the forest products industry (*145*); by 2030, forest bioenergy could double. *Eucalyptus* SRWCs can provide renewable energy feedstocks for biofuels, bioenergy, and bioproducts for tropical and subtropical regions of the U.S., namely Florida and portions of other southeastern states, Hawaii, and California (Table Ic). At present, ~50,000 ha of *Eucalyptus* SRWCs are planted in California, Hawaii, and Florida.

Short rotation woody crop *Eucalyptus* could be grown for bioenergy on up to 100,000 ha in Hawaii following guidelines from a research and development program in the 1980s (*146*). *Eucalyptus saligna* Smith in 5- and 6-year rotations and an 8-year *Eucalyptus/Albizia* mix produced 20.2, 18.6, and 26.9 or more Mg ha^{-1} yr^{-1}, respectively. Chipped *Eucalyptus* biomass was most expensive for the 5-year rotation and least for the 6-year rotation. Short- and long-term improvement programs were not implemented before program termination in 1988, but subsequent efforts by various agencies have identified promising genotypes in several species. About 9,000 ha of *Eucalyptus* plantations established since 1996 are producing over 40 m^3 ha^{-1} yr^{-1} in the most productive areas (*147*).

Due to Florida's challenging climatic and edaphic conditions, much SRWCs emphasis has been on *Eucalyptus* tree improvement for adaptability to infertile soils and damaging freezes. *Eucalyptus grandis* Hill ex. Maiden is now grown commercially in southern Florida for mulchwood and can be used in central Florida (Figure 1) (*148*), while *E. amplifolia* Naudin is suitable from central Florida into the lower Southeast. On suitable sites and/or with intensive culture, they may reach harvestable size in as few as three years (*149*). *Eucalyptus* SRWCs are promising for cofiring in coal-based power plants in central Florida. By combining superior clones (*150*), suitable culture (*148*), innovative harvesting (*148*), and efficient conversion, these two species have considerable potential in Florida. As in other SRWC development situations, research on genetics, spacing, fertilization, planting, control of pests and diseases, forest management, etc., will be essential for achieving high SRWC productivity.

Key aspects of promising *Eucalyptus* species are summarized here, including biology, genetics and tree improvement, silviculture, and the opportunities they afford as SRWCs.

Biology

Eucalypts are successful SRWCs because of their fast growth and environmental tolerance due to attributes such as indeterminate growth, coppicing, lignotubers, drought/fire/insect resistance, and/or tolerance of soil acidity and low fertility, and many have desirable wood properties for bioenergy production. While the biological traits of all currently promising *Eucalyptus* SRWCs are somewhat common, *E. grandis*, *E. amplifolia*, *E. benthamii* Maiden et Cambage, *E. macarthurii* Deane et Maiden, and *Eucalyptus* hybrids still differ in significant ways (Table V)

Table V. Relative biological characterizations of *Eucalyptus* species with high potential for bioenergy production in the southeastern United States. See text for species' authorities and additional descriptions

Characteristic	*E. grandis*	*E. amplifolia*	*E. benthamii*	*E. macarthurii*	*Hybrids*
Max. growth rate yr^{-1}	6 m	5 m	5 m	4 m	7 m
Site tolerance	Wide	Moderate	Wide	Moderate	Wide
Fertilizer response	High	Moderate	Moderate	Moderate	High
Age to seed production	Short	High	High	High	n/a
Quantity of seed produced	High	Limited	Moderate	Moderate	n/a
Ease of vegetative propagation	Easy	Difficult	Difficult	Difficult	Easy
Cold tolerance	Limited	High	High	High	Moderate
Coppicing	Limited	High	High	High	High
Wood density	Moderate	Moderate	Moderate	Moderate	Moderate

The indeterminate growth of eucalypts coupled with a range in inherent cold tolerance puts many otherwise desirable species at risk in subtropical climates with highly variable temperatures and freezes, such as the southeastern U.S. Species/ sources whose natural distributions include similar low temperatures, temperature fluctuations, and rainfall patterns tend to match exotic environments best.

As monoecious species with varying tendencies to inbreed, eucalypts often produce non-uniform seedling populations. Thus, seedling-based plantations can be less productive than clonal plantations due to poor growth of as much as 25% of the trees.

Eucalypts that vegetatively propagate easily are ideal for combining superior growth, pest resistance, cold tolerance, etc. Clonal plantations of highly selected *E. grandis* and related hybrids, for example, are common across the world.

Genetics and Tree Improvement

Eucalyptus species are ideal for genetic improvement because many typically propagate easily, have short generation intervals and broad genetic variability, and may be genetically engineered. The species/cultivars/hybrids with documented bioenergy potential in the Southeast are described below and in Table Ic and Table V. A total of 79 accessions of 35 species are being evaluated in 2010 and 2011 at 13 sites from Texas in the west to North Carolina in the north and south through Florida (*151*).

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E. grandis. Genetic improvement of *E. grandis* for Florida conditions started in the 1960s. Substantial improvements in the species' growth, form, and freeze resilience were achieved, culminating in the release in 2009 of the commercial cultivars E.nergy™ G1, G2, G3, and G4 (*150*). While G1, G2, G3, and G4 have exceptional growth rate, stem form, freeze tolerance, and coppicing ability compared to 4th-generation *E. grandis* seedlings, the four cultivars have important differences in these characteristics, their genetics, and wood properties. Planted at five locations throughout peninsular Florida in 2009, the cultivars survived well, were up to 6.1 m tall in 8 months, and typically tolerated the exceptionally cold weather of January and February 2010. Their deployment expanded in 2010, and they will be widely available as commercial SRWCs in southern, central, and even northern Florida. Research is developing even more superior *E. grandis* cultivars with desirable wood properties and pest resistance.

E. amplifolia. Genetic improvement of *E. amplifolia* for Florida began in the 1980s. Significant gains have been made in growth, form, and freeze resistance, and 1st- and 2nd-generation seedling seed orchards are established. Clonal selections have been made and are under evaluation. Improved trees were generally undamaged by the January and February 2010 freezes. In an intensive culture study near Sumterville, 7-year-old *E. amplifolia* yielded 42 green Mg ha^{-1} yr^{-1}.

E. benthamii. The species has a limited range in Australia, but trees within that range are abundant. The species is tolerant to freezing temperatures and is planted in southern Brazil on high elevation sites. *Eucalyptus benthamii* was first tested in the southern U.S. in the early 1990s by Westvaco Corp. As in Brazil, it shows very good tolerance to freezing temperatures and has survived temperatures as low as -12 °C with minimal damage (ArborGen internal data). Genetic improvement in the U.S. has been limited to open-pollinated mother tree tests and within-family tree selection to establish seedling seed orchards. The first progeny tests of this material were planted by ArborGen and collaborating companies in 2009. Seedlings from the top families have produced up to 34.8 green Mg ha^{-1} yr^{-1} at 6 years in a trial in South Carolina. Average yields are predicted to be 27 to 36 Mg ha^{-1} yr^{-1} on a 7 year rotation based on ArborGen and MeadWestvaco internal data. This species has demonstrated a wide site and climate adaptability in Coastal Plain plantings from Texas to South Carolina.

E. macarthurii. *Eucalyptus macarthurii* has been widely tested and planted in South Africa. It was also one of four species identified as having the most cold tolerance among several species tested by North Carolina State University at multiple locations in Florida, Georgia, South Carolina, and Alabama. Great improvements in forest productivity and frost tolerance have been attained since the first seedlots were planted in the U.S. Recently, new genetic trials of seedlings from improved mother trees are providing encouraging results. Significant improvements can be made in frost tolerance and growth rates by selecting the best families for plantation establishment. In a 0.8-ha planting in South Carolina, 8-year-old *E. macarthurii* produced 22 green Mg ha^{-1} yr^{-1} of clean chips.

Eucalyptus hybrids. A genetically engineered hybrid of *E. grandis* × *E. urophylla* S.T. Blake with genes for cold tolerance, lignin biosynthesis, and/or fertility is currently in the U.S. regulatory approval process (*152*). In field tests,

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these trees have survived temperatures as low as 6 °C, which allows them to be planted south of Interstate-10. The variety is well known for its high quality fiber and also excels at biomass production. Furthermore, this *Eucalyptus* can be planted on marginal lands. In traditional pulpwood management systems, this hybrid is predicted to produce 34 to 43 green Mg ha^{-1} yr^{-1} on a seven year rotation. Planted in a biomass management system, this productivity can potentially be increased to 43 to 52 green Mg ha^{-1} yr^{-1}. Further incorporation of growth genes may result in a four year rotation.

Efforts to identify regions of the *Eucalyptus* genome that regulate biomass growth and wood quality have been largely successful (*143*). As biotechnology and genomics research have allowed for once inconceivable achievements, genetic and genomics studies will likely discover most genes regulating significant portions of the heritable variation of biomass productivity and wood property traits. Ultra low sequencing reaction volumes suggest that a *Eucalyptus* genome could be sequenced in less than a day for a few hundred dollars, making it then possible to identify superior genotypes based on their genotype across multiple critical loci. For example, cinnamoyl CoA-reductase is a significant determinant of fiber properties in *Eucalyptus*. Several current studies are identifying genes of value for bioenergy, particularly those involved in the lignin and carbohydrate/cellulose pathways. Once genotyping assay methods are sufficiently cost effective to permit rapid screening of progenies in breeding programs, genotypes that combine the optimal alleles for bioenergy can be reliably identified.

Silviculture

Eucalyptus is promising for bioenergy production in the southern U.S. Cost estimates for production and delivery range from \$65 to \$79 dry Mg^{-1} (*153*). Since productivity greatly affects delivered cost, high productivity sites and systems should be favored. Shorter rotation lengths, more freeze-tolerant trees, and higher stand tree density combined with good silvicultural practices can improve productivity.

The silviculture of all *Eucalyptus* SRWCs involves many common necessities and considerations: site selection and preparation, propagule quality, weed control, spacing, fertilization, rotation length/harvest time, and coppicing. Failure in any one of these areas will severely impact productivity. For example, poor site selection, inadequate site preparation, inferior propagules, lack of weed control, improper spacing, infertility, or wrong season of harvest can, at worst, each lead to failed plantations.

Site selection and preparation are the initial critical silvicultural choices. Naturally fertile sites are ideal for *Eucalyptus*, with former and marginal agricultural sites often being very suitable. Previously forested sites need to be thoroughly cleared of debris and stumps. Poorly drained sites may require bedding and/or subsoiling. Nutrient deficiencies, most notably phosphorus (P), should be corrected. All these activities should be completed well before planting begins.

Once the appropriate species and/or genotype is chosen for the site, propagule quality needs to be ensured. The ideal containerized propagule should have a well developed, solid root ball with a firm, upright stem about 30 cm in length. Underdeveloped or overdeveloped propagules are both undesirable for achieving good survival and growth.

Control of competition within eucalypt plantations can be more difficult and expensive than in pine plantations because of the sensitivity of seedlings to the herbicides. Efforts are continuing at University of Florida and Louisiana State University to either develop or recognize chemicals that are effective on weeds and more tolerable to crop trees. In the meantime, attention to detail in applying herbicides to eucalypt plantations is critical.

Herbicides for herbaceous weed control applied over the top of planted seedlings should be applied very early in the growing season. Based on specific site characteristics, herbicides can be broadcast over an entire tract by hand, helicopter, or rubber-tired equipment. Banded applications of herbicides, at least two feet on each side of the seedlings, can be applied with rubber-tired equipment or by hand.

Spacing influences tree size, yield, and time to harvest. Conventional densities of 1500 trees ha^{-1} produce larger trees over longer rotations, while higher SRWC densities such as 3000 trees ha^{-1} maximize per ha productivities in shorter rotations.

Fertilization can be critical to achieving high productivity. *Eucalyptus* typically responds linearly to additions of N and P, which often limits growth on poorer sites. Soil amendment with wastewaters and composted waste materials can be successful. Many species are sensitive to micronutrient deficiencies, particularly boron (B) and copper (Cu).

Rotation length/harvest time can be driven by tree size requirements and harvesting equipment. Very short rotation SRWC systems may be dictated by cost effective multirow harvesters with maximum stem diameter requirements of 10 cm. Time of harvest is important with species, e.g., *E. grandis*, that have seasonal windows for successful coppicing.

Coppicing success can also be influenced by genotype and planting density. Species such as *E. amplifolia* and *E. benthamii* coppice reliably and vigorously. Multistem coppicing can be minimized by genetic selection and planting density; however, in some instances thinning of coppice sprouts may be necessary.

Sustainability

Introduction

Short rotation energy crops are one of the most sustainable sources of biomass, provided they are strategically placed on the landscape and managed with cultural practices that conserve soil and water, recycle nutrients, and maintain genetic diversity (*2*). These woody biomass sources also provide benefits such as carbon sequestration, wildlife habitat, and soil stabilization (*154–156*). Plantations also provide opportunities to reduce pressure on native forests (*157*, *158*). Overall, the sustainability of producing woody biomass from short rotation

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energy crops depends on a combination of integrated social issues (e.g., the land use debate) and biological uncertainties (e.g., genotype × environment interactions) associated with production potential of each group of species described above (*159*). Economic barriers further complicate sustainability, especially in the face of heightened consumption of non-renewable resources (*160*).

Specific sustainability criteria include protecting the resource base, maintaining biodiversity, achieving carbon and climate neutrality, and attaining a positive energy balance. Protecting the resource base requires attention to maintaining productivity and avoiding off-site impacts from pesticide or nutrient movement (*161*). In general, the conversion from cropland to forests is a net environmental gain (*162–164*). Even short-rotation tree and shrub crops result in less soil disturbance from plowing than annual crops. This will decrease soil erosion and increase soil organic matter, which should maintain or increase site productivity (*165*). Potential negative effects are very specific to management systems and the machinery used to harvest and gather material. The main environmental concerns are whether high levels of removals and more trafficking by machinery would reduce future productivity by removing too many nutrients, lowering levels of soil organic matter, compacting soil, and increasing soil erosion. For example, such concerns have been addressed by research on intensive pine silviculture and generally, we know how to avoid significant impacts. Current voluntary forestry Best Management Practices could be modified for energy plantations (*166*). A further step short of government regulation would be to require a form of third-party certification for producing biomass for energy from planted forests (*167*). The development of bioenergy from food crops has escalated concerns for conversions of native forests and engendered criticism for increasing food costs (*168*). Neither scenario applies to the short rotation energy crops described here, with the possible exception of oak-pine stands that resulted when harvested SRWC pine plantations in the South were not re-planted and understory oaks on the site were released (*12*, *111*, *169*). It is also likely that marginal farmland will be converted to SRWCs in preference over cutover forestland because of lower establishment costs and social resistance (e.g., in the upper Midwest) (*170*). The total effects on carbon balance and energy efficiency depend on not only the production and harvesting of biomass but also on the energy it produces, which depends on the efficiency of the conversion technology and products that result. Overall, these sustainability criteria are affected somewhat differently throughout respective regions of the U.S. where specific purpose-grown trees are produced (Tables Ia−Ic) (*2*), yet overarching concerns are relevant irrespective of region. Although *Salix* is illustrated as a case study below, most of the sustainability principles described are true for *Populus*, *Pinus*, and *Eucalyptus* SRWCs, as well. The major differences are centered around silvicultural prescriptions inherent to the genera.

Case Study: *Salix*

Willow biomass crops are being developed in the Northeast as sustainable systems that simultaneously produce a suite of ecological, environmental and

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social benefits in addition to a renewable feedstock for bioproducts and bioenergy (*171*, *172*). The perennial nature and extensive fine-root system of willow crops reduces soil erosion and non-point source pollution relative to annual crops, promotes stable nutrient cycling and enhances soil carbon storage in roots and the soil (*173–176*). Replacing fertilizers with biosolids or wastewater can significantly lower both the costs of growing shrub willows (*177*) and the carbon inputs into the system (*178*). Herbicide use is also significantly lower for willow crops compared to a typical corn-alfalfa rotation, because its use is confined to the first year or two during establishment (*109*). Willow crops provide rural development benefits by diversifying farm crops, creating an alternative source of income for landowners, and circulating energy dollars through the local economy (*109*).

The recommended planting scheme for willow biomass crops is designed to maintain both genetic and structural diversity across a field and the landscape. Blocks of four or more willow clones from different diversity groups should be planted in each field so that the structural and functional diversity of the system across the field is improved and any potential impact associated with pests and diseases in the future is reduced. At the landscape level willow biomass crops will be in different stages of growth each year because they are managed on three year coppice cycles that are staggered to provide a steady flow of biomass to the end users and will increase the structural diversity of the system (*171*). A study of bird diversity over several years indicated that willow biomass crops provide good foraging and nesting habitat for a diverse group of birds. Thirty-nine species of birds visited the plantations and 21 used them for nesting (*179*). The number of bird species was similar to those in early succession habitats and intact eastern deciduous forests and increased compared to open agricultural land.

Life cycle analysis (LCA) of willows indicated that it is a low-carbon fuel, because the amount of CO_2 taken up by the plants during photosynthesis is almost equal to the amount of CO_2 released during production, harvest, transportation and conversion of the biomass to bioenergy (*178*). The cycle is balanced, because only the aboveground biomass is harvested and as such the carbon that is sequestered within the roots stays in the ground. Overall greenhouse gas (GHG) emissions from willow used for electicity generation are 95% lower than coal (*180*). Willow biomass crops have a large, positive net energy ratio. Accounting for all the energy inputs into the production system, results in a net energy ratio of 1:55 (*178*). Replacing commercial N fertilizers with organic amendments, such as biosolids, the net energy ratio can increase and range from 73 to 80 (*178*). Transporting the woody biomass 40 km from the edge of the field to a coal plant where it is co-fired with coal to generate electricity results in a net energy ratio of 1:11. If a gasification conversion system is used, the net energy ratio is slightly higher (*181*).

Conclusions

Overall, intensively managed plantations representing a diverse set of short rotation species are necessary to help achieve U.S. policy that mandates the production of 16 billion gallons of cellulosic biofuels by 2022 (*1*). Paramount to the success of this achievement is testing and identification of woody biomass feedstocks that grow fast, accumulate substantial biomass, and break down to sugars easily with energy efficient technologies. The four species groups described above possess a multitude of such traits that make them attractive candidates as dedicated energy crops. Decades of breeding and selection are beginning to show significant yield and disease resistance improvements in all groups, which has the potential to result in multiple socioeconomic, environmental and ecological benefits concurrently.

Acknowledgments

We are grateful to the following people who reviewed earlier versions of the chapter: Edmund Bauer, Eric Gustafson, William Headlee Jr., and Thomas Schmidt.

References

1. U.S. Energy Independence and Security Act of 2007 (Pub. L. 110-140).
2. Vance, E . D.; Maguire, D. A.; Zalesny, R. S., Jr. *J. For.* **2010**, *108*, 183–192.
3. Zalesny, R. S., Jr.; Hall, R. B.; Zalesny, J. A.; McMahon, B. G.; Berguson, W. E.; Stanosz, G. R. *BioEnergy Res.* **2009**, *2*, 106–122.
4. Dickson, R. E.; Larson, P. R.; Isebrands, J. G. In *Proceedings of the 9th Central States Tree Improvement Conference*; Ames, IA, 1974; pp 21−34.
5. MacKay, J. J.; O'Malley, D. M.; Presnell, T.; Booker, F. L.; Campbell, M. M.; Whetten, R. W.; Sederoff, R. R. *Proc. Nat. Acad. Sci. USA* **1997**, *94*, 8255–8260.
6. Laigeng, L.; Zhou, Y.; Cheng, X.; Sun, J.; Marita, J. M.; Ralph, J.; Chiang, V. L. *Proc. Nat. Acad. Sci. USA* **2003**, *100*, 4939–4944.
7. Zhu, J. Y.; Pan, X.; Zalesny, R. S., Jr. *Appl. Microbiol. Biotechnol.* **2010**, *87*, 847–857.
8. Zhu, J. Y. U.S. Forest Service, Forest Products Laboratory, 2010; personal communication.
9. Radlein, D.; Sta, G.; Piskoriz, J.; Scott, D. S. *J. Anal. Appl. Pyrolysis* **1987**, *12*, 51 –59.
10. Mohan, D.; Pittman, C. U., Jr.; Steele, P. H. *Energy Fuels* **2006**, *20*, 848–889.
11. Brown, R. C. Iowa State University, 2010; personal communication.
12. Perlack, R.; Wright, L.; Turhollow, A.; Graham, R.; Stokes, B.; Erbach, D. Billion Ton Report by U.S. Departments of Energy and Agriculture: Washington, DC, 2005; p 78.
13. Tuskan, G. A.; DiFazio, S.; Jansson, S.; Bohlmann, J.; Grigoriev, I.; Hellsten, U.; Putnam, N.; Ralph, S.; Rombauts, S.; Salamov, A.; Schein, J.; Sterck, L.; et al. *Science* **2006**, *313*, 1596–1604.
14. Dickmann, D. I.; Stuart, K. W. *The Culture of Poplars in Eastern North America*; Department of Forestry, Michigan State University: East Lansing, MI, 1983; 168 p.
15. Stettler, R. F.; Bradshaw, H. D., Jr.; Heilman, P. E.; Hinckley, T. M. *Biology of Populus and Its Implications for Management and Conservation*; NRC

Research Press, National Research Council of Canada: Ottawa, ON, 1996; 539 p.
16. Dickmann, D. I.; Isebrands, J. G.; Eckenwalder, J. G.; Richardson, J. *Poplar Culture in North America*; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; 397 p.
17. Ragauskas, A. J.; Williams, C. K.; Davison, B. H.; Britovsek, G.; Cairney, J.; Eckert, C. A.; Frederick, J.; Hallett, J. P.; Leak, D.; Liotta, C. L.; Mielenz, J. R.; Murphy, R.; Templer, R.; Tschaplinski, T. *Science* **2006**, *311*, 484–489.
18. Kleinert, M.; Barth, T. *Energy Fuels* **2008**, *22*, 1371–1379.
19. van Haverbeke, D. E. In *Silvics of North America, 2. Hardwoods*; Burns, R. M.; Honkala, B. H., tech. coords.; Ag. Handbook 654; USDA Forest Service: Washington, DC, 1990.
20. Schreiner, E. J. USDA Forest Service Res. Pap. WO-RP-11; 1971; p 19
21. Riemenschneider, D. E.; Stanton, B. J.; Vallée, G.; Périnet, P. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. E., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 43−76.
22. Riemenschneider, D. E.; Berguson, W. E.; Dickmann, D. I.; Hall, R. B.; Isebrands, J. G.; Mohn, C. A.; Stanosz, G. R.; Tuskan, G. A. *For. Chron.* **2001**, *77*, 245–253.
23. Weiland, J. E.; Stanosz, G. R. *Plant Dis.* **2007**, *91*, 1524–1530.
24. Mohn, C. A.; Randall, W. K.; McKnight, J. S. USDA Forest Service Res. Pap. SO-RP-62; 1970, p 17.
25. Zalesny, R. S., Jr.; Hall, R. B.; Riemenschneider, D. E. *Can. J. For. Res.* **2005**, *35*, 918–929.
26. Sulaiman, A-R. R. M.S. Thesis, Iowa State University, Ames, IA, 1986.
27. Stanturf, J. A.; van Oosten, C.; Netzer, D. A.; Coleman, M. D.; Portwood, C. J. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G.; Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 153−206.
28. Perala, D. A. In *Silvics of North America, 2. Hardwoods*; Burns, R. M., Honkala, B. H., Tech. Coords.; Ag. Handbook 654; USDA Forest Service: Washington, DC, 1990.
29. Laidly, P. R. In *Silvics of North America, 2. Hardwoods*; Burns, R. M., Honkala, B. H., Tech. Coords.; Ag. Handbook 654; USDA Forest Service: Washington, DC, 1990.
30. Hall, R. B.; Hilton, G. D.; Maynard, C. A. *J. For.* **1982**, *80*, 291–294.
31. Semen, E.; Kuo, M.; Su, Y. C.; Hall, R. B.; Stokke, D. D. *Wood Fiber Sci.* **2001**, *33* (1), 140–147.
32. Balatinecz, J. J.; Kretschmann, D. E. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 277−291.
33. Zalesny, R. S., Jr.; Bauer, E. O.; Hall, R. B.; Zalesny, J. A.; Kunzman, J.; Rog, C. J. *Int. J. Phytoremed.* **2005**, *7*, 177–197.
34. Zalesny, J. A.; Zalesny, R. S., Jr.; Wiese, A. H.; Sexton, B.; Hall, R. B. *Environ. Pollut.* **2008**, *155*, 72–80.

35. Zalesny, J. A.; Zalesny, R. S., Jr.; Wiese, A. H.; Sexton, B. T.; Hall, R. B. *J. Sustainable For.* **2008**, *27*, 303–327.
36. Zalesny, J. A.; Zalesny, R. S., Jr.; Coyle, D. R.; Hall, R. B. *For. Ecol. Manage.* **2007**, *248*, 143–152.
37. Mirck, J.; Isebrands, J. G.; Verwijst, T.; Ledin, S. *Biomass Bioenergy* **2005**, *28*, 219–228.
38. Farmer, R. E., Jr. In *Biology of Populus and Its Implications for Management and Conservation*; Stettler, R. F., Bradshaw, H. D. Jr., Heilman, P. E., Hinckley, T. M., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 1996; pp 33−55.
39. Rajora, O. M.; Zsuffa, L. *Genome* **1990**, *33*, 44–49.
40. Eckenwalder, J. E. In *Biology of Populus and Its Implications for Management and Conservation*; Stettler, R. F., Bradshaw, H. D. Jr., Heilman, P. E., Hinckley, T. M., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 1996; pp 7−32.
41. Stettler, R. F.; Zsuffa, L.; Wu, R. In *Biology of Populus and Its Implications for Management and Conservation*; Stettler, R. F., Bradshaw, H. D. Jr., Heilman, P. E., Hinckley, T. M., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 1996; pp 87−112.
42. Dickmann, D. I. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 1−42.
43. Braatne, J. H.; Rood, S. B.; Heilman, P. E. In *Biology of Populus and Its Implications for Management and Conservation*; Stettler, R. F., Bradshaw, H. D. Jr., Heilman, P. E., Hinckley, T. M., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 1996; pp 57−85.
44. Farmer, R. E., Jr. *Silvae Genet.* **1964**, *13*, 116–118.
45. Kaul, R. B.; Kaul, M. N. *Southwest Nat.* **1984**, *29*, 265–269.
46. Luxova, M.; Lux, A. *Biol. Plant.* **1981**, *23*, 285–290.
47. Luxova, M.; Lux, A. *Biol. Plant.* **1981**, *23*, 401–405.
48. Geyer, W. A. *Biomass Bioenergy* **2006**, *30*, 778–783.
49. Zasada, J. C.; David, A. J.; Gilmore, D. W.; Landhäusser, S. M. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 119−151.
50. Hall, R. B.; Sabatti, M.; Scarascia-Mugnozza, G.; Anselmi, N. In *Proceedings of the Northern Forest Genetics Association* 1994, Vol. 2, pp 22−31.
51. Zsuffa, L. In *Symposium on Interspecific and Interprovenance Hybridization in Forest Trees, Proceedings of the 14th Meeting of the Canadian Tree Improvement Association*; Fowler, D. P., Yeatman, C. W., Eds.; Fredericton, New Brunswick, Canada, 1975; pp 107−123.
52. Guries, R. P.; Stettler, R. F. *Silvae Genet.* **1976**, *25*, 37–43.
53. Gaget, M.; Saïd, C.; Dumas, C.; Knox, R. B. *J. Cell Sci.* **1984**, *72*, 173–184.
54. Villar, M.; Gaget, M.; Saïd, C.; Knox, R. B.; Dumas, C. *J. Cell Sci.* **1987**, *87*, 483–490.

55. Eckenwalder, J. E. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G.; Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 331−382.
56. Ronald, W. G. *Silvae Genet.* **1982**, *31*, 94–99.
57. Eckenwalder, J. E. *Can. J. Bot.* **1984**, *62*, 325–335.
58. Hall, R. B. *Tree Physiol.* **1994**, *14*, 899–909.
59. Bae, H. H.; Kang, H. D.; Hall, R. B. *Korean J. Plant Res.* **2004**, *7* (1), 78–87.
60. Duvick, D. N. In *XX Congresso Nacional de Milho e Sorgo*; Goiania, Goias, Brasil, July 25−29, 1994.
61. Chapple, C.; Ladisch, M.; Meilan, R. *Nat. Biotechnol.* **2007**, *25* (7), 746–748.
62. Coyle, D. R.; McMillin, J. D.; Hall, R. B.; Hart, E. R. *Agric. For. Entomol.* **2002**, *4*, 293–300.
63. Coyle, D. R.; McMillin, J. D.; Krause, S. C.; Hart, E. R. *J. Econ. Entomol.* **2000**, *93*, 713–720.
64. Han, K.-H.; Meilan, R.; Ma, C.; Strauss, S. H. *Plant Cell Rep.* **2000**, *19*, 315–320.
65. Tabor, G. M.; Kubisiak, T. L.; Klopfenstein, N. B.; Hall, R. B.; McNabb, H. S., Jr. *Phytopathology* **2000**, *90*, 1039–1042.
66. Coyle, D. R.; Hart, E. R.; McMillin, J. D.; Rule, L. C.; Hall, R. B. *For. Ecol. Manage.* **2008**, *255*, 3365–3372.
67. Einspahr, D. W.; Benson, M. K.; Peckham, J. R. *Silvae Genet.* **1963**, *12*, 51–58.
68. Son, S. H.; Moon, H. K.; Hall, R. B. *Plant Sci.* **1993**, *90* (1), 89–94.
69. Newcombe, G.; Ostry, M.; Hubbes, M.; Perinét, P.; Mottet, M-J. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 249−276.
70. Smith, J. A.; Blanchette, R. A.; Ostry, M. E.; Anderson, N. A. *Am. Phytopathol. Soc.* **2002**, *86* (5), 462–469.
71. Little, E. L., Jr.; Brinkman, K. A.; McComb, A. L. *For. Sci.* **1957**, *3*, 253–262.
72. Goerndt, M. E.; Mize, C. *North. J. Appl. For.* **2008**, *25* (2), 82–86.
73. Green, B. K. M.S. Thesis, Iowa State University, Ames, IA, 1998, 63 p.
74. Hall, R. B.; Ruigu, S. In *Fifth International Poplar Symposium 2010*; Internatinal Union of Forestry Research Organizations (IUFRO): Viterbo, Italy, 2010, p 75.
75. Hall, R. B.; Colletti, J. P.; Schultz, R. C.; Faltonson, R. R.; Kolison, S. H., Jr.; Hanna, R. D.; Hillson, T. D.; Morrison, J. W. USDA Forest Service Gen. Tech. Rep. NC-GTR-140; 1989, pp 211−219.
76. Eaton, J. In *IEA Bioenergy Task 30 Workshop*; Guelph, Ontario, Canada, August 13, 2007.
77. Hall, R. B.; Hart, E. R.; Peszlen, I. In *Molecular Breeding of Woody Plants*; Morohoshi, N, Komamine, A., Eds.; Elsevier Science B.V.: 2001, pp 229−238.

78. Stanosz, G. R; Kruger, E. L.; Isebrands, J. G. In *BioEnergy '98: Expanding Bioenergy Partnerships*: Madison, WI, October 4−8, 1998.
79. Gruenewald, H.; Brandt, B. K. V.; Uwe Schneider, B.; Bens, O.; Kendzia, G.; Huttl, R. F. *Ecol. Eng.* **2007**, *29*, 319–328.
80. Zenone, T.; Migliavacca, M.; Montagnani, L.; Seufert, G.; Valentini, R. 2007. http://www.fao.org/forestry/13710-1-0.pdf (Last accessed on 11/16/10).
81. Hall, R. B.; Headlee, W.; Ruigu, S. In *Fifth International Poplar Symposium 2010*; Internatinal Union of Forestry Research Organizations (IUFRO): Viterbo, Italy, 2010, p 98.
82. Headlee, W. L.; Hall, R. B.; Zalesny, R. S., Jr. In *Fifth International Poplar Symposium 2010*; Internatinal Union of Forestry Research Organizations (IUFRO): Viterbo, Italy, 2010, p 129.
83. Hall, R. B. In *Proceedings of the 1993 Joint Meeting of the Poplar Councils of the United States and Canada*; Bronstein, R., Ed.; Poplar Council of Canada: 1993; pp 68−73.
84. Zsuffa, L.; Sennerby-Forsse, L.; Weisgerber, H.; Hall, R. B. In *Clonal Forestry II, Conservation and Application*; Ahuja, M. R., Libby, W. J., Eds.; Springer Verlag: Berlin, 1993; pp 91−119.
85. Börjesson, P. *Biomass Bioenergy* **1999**, *16*, 137–154.
86. Volk, T. A.; Abrahamson, L. P.; Nowak, C. A.; Smart, L. B.; Tharakan, P. J.; White, E. H. *Biomass Bioenergy* **2006**, *30*, 715–727.
87. Richardson, J.; Cooke, J. E. K.; Isebrands, J. G.; Thomas, B. R.; van Rees, K. C. J. *Can. J. Bot.* **2007**, *85*, 1136–1146.
88. Zsuffa, L. *Biomass* **1990**, *22*, 35–47.
89. Buchholz, T. S.; Volk, T. A. *BioEnergy Res.*, in press, DOI:10.1007/s12155-010-9103-5
90. Smart, L. B.; Cameron, K. D.; Volk, T. A.; Abrahamson, L. P. *NABC Report 19*; *Agricultural Biofuels*; National Agricultural Biotechnology Council: Ithaca, NY, 2008; pp 85−92.
91. Newsholme, C. *Willows, The Genus Salix*; Timber Press: Portland, OR, 1992; 224 p.
92. Kuzovkina, Y. A.; Weih, M.; Romero, M. A.; Charles, J.; Hurst, S.; McIvor, I.; Karp, A.; Trybush, S.; Labrecque, M.; Teodorescu, T. I.; Singh, N. B.; Smart, L. B.; Volk, T. A. In *Horticultural Reviews*; Janick, J., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, 2008; Vol. 34, pp 447−489.
93. Dickmann D. I.; Kuzovkina, J. In *Poplars and Willows in the World*; Isebrands, J. G., Richardson, J., Eds.; Working Paper IPC/9-2. FAO, Rome, Italy, 2008.
94. Smart, L. B.; Cameron, K. D. In *Genetic Improvement of Bioenergy Crops*; Vermerris, W., Ed.; Springer: 2008, pp 347−376.
95. Nordman, E. E.; Robison, D. J.; Abrahamson, L. P.; Volk, T. A. *For. Ecol. Manage.* **2005**, *217*, 307–318.
96. Hunter, T.; Royle, D. J.; Arnold, G. M. *Ann. Appl. Biol.* **1996**, *129*, 1–12.
97. Peacock, L.; Hunter, T.; Turner, H.; Brain, P. *J. Appl. Ecol.* **2001**, *38*, 1070–1081.

98. Collins, C. M.; Fellowes, M. D. E.; Sage, R. B.; Leather, S. R. *Agric., Ecosyst. Environ.* **2001**, *3*, 183–189.
99. Argus, G. W. *Systematic Botany Monographs*; American Society of Plant Taxonomists: Ann Arbor, MI, 1997; 121 p.
100. Argus, G. W. Botanical Electronic News (BEN) #227. 1999. http://www.ou.edu/cas/botany-micro/ben227.html (Last accessed on 11/16/10).
101. Lin, J. Z.; Zsuffa, L. *Silvae Genet.* **1993**, *42*, 126–131.
102. Cameron, K. D.; Phillips, I. S.; Kopp, R. F.; Volk, T. A.; Maynard, C. A.; Abrahamson, L. P.; Smart, L. B. *BioEnergy Res.* **2008**, *1*, 80–90.
103. Tharakan, P. J.; Volk, T. A.; Lindsey, C. A.; Abrahamson, L. P.; White, E. H. *Energy Policy* **2005**, *33*, 337–347.
104. Adegbidi, H. G.; Volk, T. A.; White, E. H.; Abrahamson, L. P.; Briggs, R. D.; Bickelhaupt, D. H. *Biomass Bioenergy* **2001**, *20*, 399–411.
105. Adegbidi, H. G.; Briggs, R. D.; Volk, T. A.; White, E. H.; Abrahamson, L. P. *Biomass Bioenergy* **2003**, *25*, 389–398.
106. Volk, T. A.; Kiernan, B. D.; Kopp, R.; Abrahamson, L. P. In *Fifth Biomass Conference of the Americas*; Orlando, FL, 2001.
107. Volk, T. A. Ph.D. Thesis, SUNY-ESF, Syracuse, NY, 2002.
108. Labrecque, M.; Teodorescu, T. I. *Biomass Bioenergy* **2005**, *29*, 1–9.
109. Volk, T. A.; Luzadis, V. In *Renewable Energy from Forest Resources in the United States*; Routledge Press: New York, 2009; pp 238−260.
110. Prestemon, J. P.; Abt, R. C.USDA Forest Service Gen. Tech. Rep SRS-GTR-53; 2002, pp 299−325.
111. Zhang, D.; Polyakov, M. *Biomass Bioenergy* **2010**, *34* (12), 1643–1654.
112. Stanturf, J. A.; Kellison, R. C.; Broerman, F. S.; Jones, S. B. *J. For.* **2003**, *101* (3), 26–31.
113. Stanturf, J. A.; Kellison, R. C.; Broerman, F. S.; Jones, S. B. *For. Policy Econ.* **2003**, *5* (4), 407–419.
114. Allen, H. L.; Fox, T. R.; Campbell, R. G. *South. J. Appl. For.* **2005**, *29* (2), 62–69.
115. Carter, M. C.; Foster, C. D. *For. Ecol. Manage.* **2006**, *227* (1-2), 137–144.
116. Fox, T. R.; Jokela, E. J.; Allen, H. L. *J. For.* **2007**, *105* (7), 337–347.
117. Jokela, E. J.; Dougherty, P. M.; Martin, T. A. *For. Ecol. Manage.* **2004**, *192* (1), 117–130.
118. McKeand, S.; Mullin, T.; Byram, T.; White, T. *J. For.* **2003**, *101* (3), 32–37.
119. Wear, D. N.; Greis, J. G. In *The Southern Forest Resource Assessment: Final Report*; USDA Forest Service, Southern Research Station: Asheville, NC, 2002; 675 p.
120. Wear, D. N.; Newman, D. H. *J. For.* **2004**, *102* (8), 25–31.
121. Wear, D. N.; Greis, J. G. *J. For.* **2002**, *100* (7), 6–15.
122. Butler, B. U.S. Forest Service, Northern Research Station, 2010; personal communication.
123. Skog, K. E.; Stanturf, J. A. Forest Biomass Sustainability and Availability. Zho, J. Y., Zhang, X., Pan, X., Eds.; ACS Syposium Series 1067; American Chemical Society: Washington, DC, 2011; Chapter 1.
124. Colbert, S. R.; Jokela, E. J.; Neary, D. G. *For. Sci.* **1990**, *36* (4), 995–1014.

125. Burkes, E. C.; Will, R. E.; Barron-Gafford, G. A.; Teskey, R. O.; Shiver, B. *For. Sci.* **2003**, *49* (2), 224–234.
126. Jokela, E. J.; Wilson, D. S.; Allen, J. E. *South. J. Appl. For.* **2000**, *24* (1), 23–30.
127. Borders, B. E.; Bailey, R. L. *South. J. Appl. For.* **2001**, *25*, 69–74.
128. Roth, B. E.; Jokela, E. J.; Martin, T. A.; Huber, D. A.; White, T. L. *For. Ecol. Manage.* **2007**, *238* (1−3), 175–188.
129. McKeand, S. E.; Jokela, E. J.; Huber, D. A.; Byram, T. D.; Allen, H. L.; Li, B.; Mullin, T. J. *For. Ecol. Manage.* **2006**, *227* (1−2), 178–184.
130. Berisford, C. W.; Kulman, H. M. *For. Sci.* **1967**, *13*, 428–438.
131. Nowak, J. T.; Berisford, C. W. *J. Econ. Entomol.* **2000**, *93* (2), 336–341.
132. Coyle, D. R.; Nowak, J. T.; Fettig, C. J. *J. Entomol. Sci.* **2003**, *38* (4), 621–630.
133. Cade, S. C.; Hedden, R. L. *South. J. Appl. For.* **1987**, *11*, 128–133.
134. Ross, D. W.; Berisford, C. W.; Godbee, J. F. *For. Sci.* **1990**, *36*, 1105–1118.
135. Nelson, C. D.; Kubisiak, T. L.; Amerson, H. V. *For. Pathol.* **2010**, *40* (1), 64–72.
136. Whetten, R. W.; Kellison, R. *J. For.* **2010**, *108* (4), 193–201.
137. Albaugh, T. J.; Lee Allen, H.; Dougherty, P. M.; Johnsen, K. H. *For. Ecol. Manage.* **2004**, *192* (1), 3–19.
138. Adegbidi, H. G.; Jokela, E. J.; Comerford, N. B. *For. Ecol. Manage.* **2005**, *218* (1-3), 245–258.
139. Scott, D. A.; Tiarks, A. *South. J. Appl. For.* **2008**, *32* (1), 33–37.
140. ArborGen FlexStand System Guide. http://www.arborgen.us/uploads/catalog/FlexStand_Brochure_v10.pdf (Last accessed on 11/16/10).
141. Catchlight Intercropping. http://www.catchlightenergy.com/Feedstocks.aspx (Last accessed on 11/16/10).
142. Sims, R. E. H.; Hastings, A.; Schlamadinger, B.; Taylor, G.; Smith, P. *Global Change Biol.* **2006**, *12* (11), 2054–2076.
143. Rockwood, D. L.; Kirst, M.; Isebrands, J. G.; Zhu, J. Y. In *Handbook of Bioenergy Crop Plants*; Kole, C., Joshi, C. P., Shonnard, D. R., Eds.; CRC Press, Taylor and Francis Group: 2011, in press.
144. Sims, R. E. H. *Mitigation Adapt. Strategies Global Change* **2003**, *8* (4), 349–370.
145. Wright, L. *Biomass Bioenergy* **2006**, *30*, 706–714.
146. Whitesell, C. D.; DeBell, D. S.; Schubert, T. H.; Strand, R. F.; Crabb, T. B. USDA Forest Service Gen. Tech. Rep PSW-GTR-137; Albany, CA, 1992; 30 p.
147. Forest Solutions. www.hawaiiforest.com/commercial_forestry.htm (Last accessed on 11/16/10).
148. Rockwood, D. L.; Rudie, A. W.; Ralph, S. A.; Zhu, J. Y.; Winandy, J. E. *Int. J. Mol. Sci.* **2008**, *9*, 1361–1378.
149. Langholtz, M.; Carter, D. R.; Rockwood, D. L.; Alavalapati, J. R. R. *J. For. Econ.* **2007**, *12*, 237–249.
150. Rockwood, D. L.; Tamang, B. *Proc. Florida State Hort. Soc.* 2010, (in press).
151. Stape, J. North Carolina State University, 2010; personal communication.

152. ArborGen. http://www.arborgen.us/uploads/publications/eucalyptus-plantations.pdf; http://www.arborgen.us/uploads/tree-lines-newsletters/TreeLines_Spring10_v05_1.pdf; http://www.arborgen.us/index.php/products/product-pipeline/freeze-tolerant-eucalyptus (Last accessed on 11/16/10).
153. Gonzalez, R.; Wright, J.; Saloni, D. *Biomass Mag.* **2010**, *41*, 52–55.
154. Hansen, E. A. *Biomass Bioenergy* **1993**, *5*, 431–436.
155. Isebrands, J. G.; Karnosky, D. F. In *Poplar Culture in North America*; Dickmann, D. I., Isebrands, J. G., Eckenwalder, J. G., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, 2001; pp 207−218.
156. Moser, B. W.; Pipas, M. J.; Witmer, G. W.; Engeman, R. M. *Northwest Sci.* **2002**, *76*, 158–165.
157. Gladstone, W. T.; Ledig, F. T. *For. Ecol. Manage.* **1990**, *35*, 69–78.
158. Joslin, J. D.; Schoenholtz, S. H. *Biomass Bioenergy* **1997**, *13*, 301–311.
159. Johnson, J. M. F.; Coleman, M. D.; Gesch, R.; Jaradat, A.; Mitchell, R.; Reicosky, D.; Wilhelm, W. W. *Am. J. Plant Sci. Biotechnol.* **2007**, *1*, 1–28.
160. Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. *Proc. Nat. Acad. Sci. USA* **2006**, *103*, 11206–11210.
161. Powers, R. F. *New For.* **1999**, *17* (1), 263–306.
162. Janowiak, M. K.; Webster, C. R. *J. For.* **2010**, *108* (1), 16–23.
163. Brockerhoff, E.; Jactel, H.; Parrotta, J.; Quine, C.; Sayer, J. *Biodiversity Conserv.* **2008**, *17* (5), 925–951.
164. Carnus, J. M.; Parrotta, J.; Brockerhoff, E.; Arbez, M.; Jactel, H.; Kremer, A.; Lamb, D.; O'Hara, K.; Walters, B. *J. For.* **2006**, *104* (2), 65–77.
165. Vance, E. D. *For. Ecol. Manage.* **2000**, *138* (1−3), 369–396.
166. Shepard, J. P. *Biomass Bioenergy* **2006**, *30* (4), 378–384.
167. Lucier, A. A.; Shepard, J. P. *Biomass Bioenergy* **1997**, *13* (4-5), 193–199.
168. Runge, C. F.; Senauer, B. *Foreign Affairs* **2007**, *86* (3), 41–53.
169. Munsell, J. F.; Fox, T. R. *Biomass Bioenergy* **2010**, *34* (12), 1631–1642.
170. Zalesny, R. S., Jr.; Donner, D. M.; Coyle, D. R.; Headlee, W. L.; Hall, R. B. In *8th Biennial Short Rotation Woody Crops Operations Working Group Conference: Short Rotation Woody Crops in a Renewable Energy Future: Challenges and Opportunities*; Syracuse, NY, October 17−21, 2010.
171. Volk, T. A.; Verwijst, T.; Tharakan, P. J.; Abrahamson, L. P. *Front. Ecol. Environ.* **2004**, *2*, 411–418.
172. Rowe, R. L.; Street, N. R.; Taylor, G. *Renewable Sustainable Energy Rev.* **2008**, *13*, 271–290.
173. Ranney, J. W.; Mann, L. K. *Biomass Bioenergy* **1994**, *6*, 211–228.
174. Aronsson, P. G.; Bergstrom, L. F.; Elowson, S. N. E. *J. Environ. Manage.* **2000**, *58*, 135–45.
175. Tolbert, V. R.; Todd, V., Jr.; Mann, L. K.; Jawdy, C. M.; Mays, D. A.; Malik, R. *Environ. Pollut.* **2002**, *16*, S97–S106.
176. Ulzen-Appiah, F. Ph.D. Thesis, SUNY-ESF, Syracuse, NY, 2002.
177. Rosenqvist, H.; Dawson, W. M. *Biomass Bioenergy* **2005**, *29*, 83–92.
178. Heller, M. C.; Keoleian, G. A.; Volk, T. A. *Biomass Bioenergy* **2003**, *25*, 147–65.

179. Dhondt, A.; Wrege, P. H.; Cerretani, J.; Sydenstricker, K. *Bird Study* **2007**, *54*, 12–22.
180. Heller, M. C.; Keoleian, G. A.; Mann, M. K.; Volk, T. A. *Renewable Energy* **2004**, *29* (7), 1023–1042.
181. Keoleian, G. A.; Volk, T. A. *Crit. Rev. Plant Sci.* **2005**, *24*, 385–406.