# 15 Forest Trees

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15.1 INTRODUCTION

Interest in renewable biomass for fuel, chemicals, and materials is high (e.g., Rocha et al. 2002), as many products currently derived from petrochemicals can be produced from biomass (Sims et al. 2006). Biomass can be converted into many energy products and chemicals: e.g., alcohol by fermenting cellulose, charcoal, bio-oil, and gases by biomass pyrolysis (Khesghi et al. 2000). Biomass and biofuels technologies with the most potential in the United States include co-firing in coal-fired power plants, integrated gasification combined-cycle units in forestry, and ethanol from hydrolysis of lignocellulosics (Sims 2003). A wide range of products from woody biomass has been demonstrated in New Zealand: “value-added” chemicals, hardboards, activated carbon, animal feed, and bioenergy feedstock (Sims 2003). Using harvested biomass to replace fossil fuels has long-term significance in using forest lands to prevent carbon emissions, and bioenergy projects can contribute to slowing global climate change (Swisher 1997). The potential importance and cost-effectiveness of bioenergy measures in climate change mitigation require evaluation of cost and performance in increasing terrestrial carbon storage.

Biomass-based heat, electricity, and liquid fuels are about 14% of the world’s primary energy supply (IEA 1998), with about 25% of that in developed countries and 75% in developing countries (Parikka 2004). From an estimated 3.87 billion ha of forest worldwide, global production and use of wood fuel was about 1.753 billion m$^3$ in 1999 (Table 15.1), 90% of which was produced and consumed in developing countries.

The total sustainable worldwide annual bioenergy potential is about 100 EJ (Table 15.1), about 30% of total current global energy consumption (Parikka 2004). Annual woody biomass potential is 41.6 EJ, or 12.5% of total global energy consumption. Worldwide, less than 40% of the existing bioenergy potential is used. In all regions except Asia, current biomass use is less than the available

<table>
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<td>421</td>
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</table>

potential, especially in North America and South America. Therefore, increased woody biomass use is possible in most countries.

Although most wood currently used for bioenergy comes from natural forests, the greatest potential for increasing bioenergy production is in establishing plantations, which currently are only 5% of the world’s forest area (Table 15.1). Forest plantations have dramatically increased for the last 25 years, mainly in Asia. The area of productive forest plantations increased by 2 million ha/year from 1990 to 2000 and by 2.5 million ha/year from 2000 to 2005. *Eucalyptus*, *Pinus*, and *Populus* species are particularly suited for short rotation woody crop (SRWC) plantings, although many other forest species may also be used. Accordingly, we review current activity with, and the potential of, the main species in these three genera, with additional focus on the role and potential of biotechnology to increase *Eucalyptus* biomass production and enhance conversion to bioenergy products.

### 15.2 *Eucalyptus*

Many of over 700 *Eucalyptus* species, native primarily to Australia, have potential as biomass crops. Eucalypts are successful exotics because of their fast growth and environmental tolerance because of attributes such as indeterminate growth, coppicing, lignotubers, drought/fire/insect resistance, and/or tolerance of soil acidity and low fertility. Many eucalypts have desirable wood properties, such as high density, for bioenergy production.

With 19.6 million ha of plantations in some 90 countries (Trabedo and Wilshermann 2008; Figure 15.1), *Eucalyptus* is the most valuable and widely planted hardwood worldwide. Eucalypts

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are grown in SRWCs in tropical and subtropical Africa, South America, Asia, and Australia, and in temperate Europe, South America, North America, and Australia (Figure 15.1), but 12 countries account for nearly all of the almost 12 million ha classified as productive (FAO 2006; Table 15.1, Figure 15.1). Eucalypt planting is still intensifying, especially in tropical countries.

Four species and their hybrids from the subgenus *Symphyomyrtus* (*Eucalyptus grandis* (EG), *E. urophylla* (EU), *E. camaldulensis*, and *E. globulus*) constitute about 80% of eucalypt SRWCs worldwide. EG, EU, and EG × EU hybrids are favored in tropical and subtropical regions. EG has been planted extensively in countries such as India and South Africa, and it is grown in California, Hawaii, and Florida in the United States. *E. globulus* is best for temperate countries such as Portugal, Spain, Chile, and Australia. Eucalypt products worldwide include pulp for high quality paper (Tournier et al. 2003), poles, lumber, plywood, veneer, flooring, landscape mulch (Aaction Mulch 2007), fiberboard (Krysik et al. 2001), composites (Coutts 2005), essential oils (Barton 2007), firewood, and charcoal.

### 15.2.1 Eucalyptus Bioenergy Use and Potential Worldwide

Although eucalpts are major bioenergy contributors worldwide, their utilization by individual countries reflects a number of factors. Renewable energy incentives, greenhouse gas (GHG) emission targets, synergism with industrial waste management projects, and high oil prices are major drivers of SRWCs for bioenergy.

Bioenergy consumption is greatest in countries with heavy subsidies or tax incentives, such as Brazil and China (Wright 2006). Total bioenergy consumption in China, EU, the United States, Brazil, Canada, and Australia is 17.1 EJ. SRWCs in Brazil, New Zealand, and Australia total about 5 million ha, and SRWCs in China may be as large as 10 million ha, whereas SRWCs and other energy crops in the United States and EU are less than 100,000 ha. SRWCs have mainly been established for other than bioenergy production. Australia, Brazil, Canada, New Zealand, Sweden, the United Kingdom, and the United States are among the countries conducting SRWC research and development.

#### 15.2.1.1 Brazil

Brazil is the world’s largest bioenergy producer and consumer, with 29.6% of its energy coming from biomass in 2003, including 13.0% from firewood and charcoal (Pelaez-Samaneigo et al. 2008). With 3 million ha of *Eucalyptus* SRWCs (Rosillo-Calle 2004), it may have the most SRWCs grown specifically for energy. *Eucalyptus* planting occurred primarily from 1966 to 1989 under government incentives (Couto et al. 2004). The pulp and paper industry has more than 1.4 million ha of mainly *Eucalyptus* and pine plantations.

Wood production, especially SRWC *Eucalyptus*, is well established in Brazil (Couto et al. 2002). Brazil has about 5 million ha of sustainable forests (afforestation and reforestation), with 56% of these forests in the Southeast, where *Eucalyptus* is 64% of the area (BMME 2003). SRWC establishment targets from 2004 to 2007 included 0.8 and 1.2 million ha through small/medium farmers and through medium/large companies, respectively.

SRWC utilization is 33% for charcoal production, 13% for industrial energy, 31% for pulp and paper mills, and 23% for timber (BMME 2003). Brazil produced 7.3 million tons (225 PJ) of charcoal in 2003, of which the steel industry consumed 85% (Walter et al. 2006). SRWC *Eucalyptus* accounted for 87%, 97%, and 74% in 1997, 1999, and 2003, respectively, of the charcoal consumed by steel mills (ABRACAVE 2003).

Brazil’s forests produce about 55 million tons of firewood (Walter et al. 2006). Of this, over 40% is for charcoal (almost 580 PJ), 29% is for residential use, and 23% is for industrial and commercial uses such as steam generation. Charcoal production was 22% of industrial roundwood consumption from SRWCs in Brazil in 2006 (Pelaez-Samaneigo et al. 2008). Wood chip production for electricity and heating in Europe in 2004 was expected to be 250,000 green mt, or 3 PJ, using acacia and bark of *Eucalyptus* and *Pinus*. 
SRWCs are benefitting from decades of research and development of forest management practices including genetic improvement, spacing, fertilization, planting techniques, control of pests and diseases, and coppicing. Mean yields of *Eucalyptus* SRWCs went from 14 m$^3$/ha per year during the 1970s to the current approximately 40 m$^3$/ha per year through breeding and silvicultural practices. Up to three harvests are possible from one planting of *Eucalyptus*. In comparison to its own average productivity of 450 GJ/ha per year, one Brazilian company’s highest *Eucalyptus* productivity is 1000 GJ/ha per year, whereas in the United States, commercial forests average less than 100 GJ/ha per year and switchgrass may achieve 430 GJ/ha per year. Stumpage prices for *Eucalyptus* in Brazil were just 0.5–0.6 U.S.$/GJ (ABRACAVE 2003).

Vegetative propagation of superior clones has enhanced *Eucalyptus* productivity. Starting in the 1960s, rooted cuttings provided local site adaptation with cost and wood property advantages. Optimized and efficient transformation and recovery procedures exist for some *Eucalyptus* genotypes. Various transgenic *Eucalyptus* plantlets have been regenerated from stem or leaf segments. Micropropagation and transformation have combined with efforts to engineer novel or alter existing traits. Elite hybrid clones with superior wood quality, rapid growth, and disease resistance are also used extensively in tropical and subtropical regions of South Africa, Congo, and China.

Under Brazil’s Code of Best Practices for Planted Forests, several desirable SRWC practices are encouraged (Piketty et al. 2008). No-tillage or reduced tillage is the usual method of planting. Reduced input of chemicals is recommended. For SRWC licensing, general BMPs must be followed. Small farmers have incentives for reforesting marginal lands. In an “integrated system,” industry provides clones (seedlings) and all other agricultural materials; farmers provide land and labor.

A transition is taking place from “conventional” biomass (e.g., firewood used for cooking) to “modern” biomass (industrial heat and electricity and biofuels). In Brazil’s advanced programs for bioenergy (Lora and Andrade 2008), biomass gasification is widely applied and encouraged. At 11.3%, “modern” biomass in the Brazilian energy matrix is practically the same as traditional biomass (12.5%). On a global scale, modern biomass is only 1.73% of the whole energy consumption.

In Brazil, bioenergy is implemented at three levels: (1) low, 1–25 kWs (small communities); (2) up to 5 MWs (small communities, sawmills, furniture factories, and rice treatment plants), and (3) over 5–10 MW (sugar and alcohol plants, pulp and paper mills, and biomass thermal power plants).

Brazil ranked first in a global assessment of land potentially available to supply charcoal to the steel industry (Piketty et al. 2008). Increasing charcoal making efficiency from 330 to 450 kg/tons of wood (+36%), using 100% SRWCs by 2010, cleaner carbonization techniques, and by-products such as liquid fuels and chemicals through gases and liquids recovery will insure the continued use of charcoal (Rosillo-Calle and Bezzone 2000). A simple upgrade of traditional charcoal production can significantly increase liquid fuel output. Slow pyrolysis bio-oil can be an excellent, cost-effective and renewable liquid fuel (Stamatov and Rocha 2007). A biochar-refinery for production of charcoal, activated carbon, liquid fuel and variety of chemicals presents a possible approach for the development of biomass-based industry. Under the current levels of best practices in *Eucalyptus* SRWCs, carbonization and charcoal use, 50 million tons of steel would require 6.5 million ha of SRWCs.

When new plantations and reforestation resulting mainly from the National Programs are ready to be harvested, Brazil will have forest biomass for export. A least three big energy and pulp companies have their own ports.

Estimates of the total installed potential for electricity generation from biomass range from 2680 to 4740 MW. The total installed power is 96.63 GW of which 4.74 GW (4.9%) is from biomass. Several cogeneration plants have been built in the sugar/alcohol sector. The pulp and paper industry had potential in 2003 for 1740 MW and had excellent prospects for electric self-sustainability through cogeneration using renewable energy (wood residue, bark and black liquor). Six thermal power plants using biomass totaling 80.35 MW are being built, and 42 other units with a total power of 673.6 MW have been authorized. About 5% of SRWC *Eucalyptus* could be used to generate electricity, increasing potential output from 4000 to 8000 MW.
Some 85 million ha may be suitable for natural regeneration, farm forestry and SRWCs, but only 20 million ha could be planted by 2030 (Piketty et al. 2008). Other estimates of potential SRWC extent included 30 and 41.2 million ha. Brazilian states with available grasslands and savannas for SRWC planting include Mato Grosso, Maranhao, Tocantins, Piaui, Goias, Para, Minas Gerais, Mato Grosso do Sul, and Bahia, with Piaui preeminent for sustainable *Eucalyptus* SRWCs involving small and medium landowners.

Brazil has very favorable land, climate, policies, and experience in highly productive SWRCs for the pulp and paper industry and increasingly for bioenergy. Given the prominence of current and future *Eucalyptus* SRWCs (Table 15.1) in areas with large energy needs and production potential, *Eucalyptus* can be a significant contributor of a range of energy products. *Eucalyptus* wood is even used for making activated carbon adsorbents for liquid-phase applications such as water and wastewater treatment. In the tropics and subtropics where *Eucalyptus* species are already widely planted, their further deployment for energy products is especially likely.

### 15.2.1.2 China

In 2002, China’s 7.5 EJ of bioenergy consumption (16.5% of total energy), including approximately 200 million tons of firewood, more than doubled that of any other country and is increasing (Wright 2006). In 2000, China led the world in afforestation. Plantations totaled 4.67 million ha in 2002, though only a portion was likely SRWCs for energy. In 2006, SRWCs were up to 10 million ha, mostly in southern China. Goals for 2010 and 2015 were some 13.5 million ha of “fast growing plantations.” China’s 24 million ha of new plantations and natural regrowth transformed a century of net carbon emissions by forestry to net gains of 0.19 Pg C per year, offsetting 21% of its fossil fuel emissions in 2000 (Canadell and Raupach 2008).

Commercial biomass energy is only about 14% of the total energy consumed in China (Wright 2006). China has very abundant but inefficiently used bioenergy resources. Bioenergy is mainly used in rural areas, accounting for 70% of rural energy consumption. Started in 1981, firewood plantations totaled 4.95 million ha by 1995 and provided 20–25 million tons of firewood each year that largely alleviated the rural energy crisis. Now, 210 million m³ of firewood are produced annually, equivalent to 120 million tons of standard coal.

China’s forest area of 175 million ha in 2003 contained a forest volume of approximately 12 billion m³. Plantations were approximately 53 million ha with a volume of 1.5 billion m³. Still, China faced a deficiency of industrial timber, as industrial roundwood consumption in 2004 was 310 million m³ and was expected to reach 472 million m³ in 2020. Fast-growing, high-yielding trees for industrial plantations are needed to ease the deficiency.

*Eucalyptus* species are very important for industrial plantations in China (Xiong 2007). China now has the second largest *Eucalyptus* plantation in the world, just behind Brazil. First introduced into China in 1890 as ornamental and landscape trees, 70 species have been successful, and over 1.8 million ha of *Eucalyptus* are established in the Southeast. More than 20 years of selection and breeding in collaboration with Australian researchers resulted in 135 seed sources and more than 600 clones for Guangxi province. Through tests, approximately 2000 elite trees in 500 families were selected for the first breeding populations of 10 species including *EU, E. tereticornis, EG, EU × EG, E. pellita, E. camaldulensis,* and *E. dunnii*. Genetic gains of 15–25% were realized after the first generation. By crossing 12 species, good hybrids were selected, with the best families and clones growing substantially better. Cold hardy crosses such as *EU × E. camaldulensis* and *E. tereticornis* have also been created. Concurrent with a broad research program, seed orchards and clonal gardens were created for selected species. The biggest propagation center is in Guangxi, which provides superior seed or vegetative propagules for southern *Eucalyptus* plantations.

In China, eucalypt plantations are harvested for pulpwood, fiberboard, sawlogs, roundwood, veneer, fuelwood and oil. Residues and leaf litter are used for fuelwood. Eucalypt oil production is primarily confined to cooler, temperate regions, where up to 150,000 ha of plantations are used for oil.
Although China has considerable bioenergy potential, many factors may constrain its effective use. To overcome these problems, China has formed a bioenergy development strategy. In China’s strategic framework for energy development, bioenergy would become the major component in a sustainable energy system that may account for 40% or more of total energy consumption by 2050 (Wright 2006).

15.2.1.3 India

Bioenergy accounts for nearly 25% of total primary energy in India and over 70% of rural energy (Ravindranath et al. 2007). Consumption of fuelwood, the dominant biomass fuel, is 162–298 million tons. Only about 8% of the fuelwood is considered sustainable, and private plantations and trees account for almost 50%.

Although India’s current bioenergy use is relatively inefficient, modern bioenergy technologies are opportunities for meeting energy needs, improving the quality of life, and protecting the environment. These technologies include biomass combustion and gasification for power generation and liquid (biodiesel and ethanol) and gaseous (biogas) fuels. The dominant bioenergy option is power generation using woody biomass, largely from SRWCs.

India has a large renewable energy promotion program with several financial and policy incentives. Total installed biomass combustion and gasification capacity is 738 MW, with a potential of over 20,000 MW. However, technical, financial and policy barriers limit the large-scale production of biomass for power generation.

Critical to realizing the technical and economic potential of bioenergy is a sustainable biomass supply, including woody biomass. Forests occupy approximately 64 million ha of India, and forest cover, including SRWCs (Table 15.2), home gardens, and agroforestry, is 77 million ha (23.5% of the country). India has implemented one of the largest afforestation programs in the world, using largely Eucalyptus, Acacia, Casuarina, Populus, and teak to meet fuelwood, industrial wood, and timber needs. From 1980 to 2005, approximately 34 million ha were afforested at an annual rate of 1.32–1.55 million ha, whereas deforestation was 0.272 million ha per year (Ravindranath et al. 2001). Consequently, the 10 GtC of carbon in Indian forests has nearly stabilized or is increasing.

<table>
<thead>
<tr>
<th>Country</th>
<th>Species</th>
<th>0–5</th>
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<th>10–20</th>
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<td>0.7</td>
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<tr>
<td></td>
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A sustainable forestry scenario aimed at meeting the projected biomass demands, halting deforestation, and regenerating degraded forests was developed (Ravindranath et al. 2001). Excluding the land required for traditional fuelwood, industrial wood, and timber production, and considering only potential land categories suitable for plantation forestry, 41–55 million ha is available for SRWCs. About 12 million ha is adequate to meet the incremental fuelwood, industrial wood, and timber requirements projected to 2015. An additional 24 million ha is available for SRWCs with sustainable biomass potential of 158–288 million t annually. Other estimates vary from 41–130 million ha. Marginal cropland and long-term fallow lands are also available for SRWCs. Assuming a conservative 35 million ha of SRWCs producing 6.6–12 tons/ha per year, the additional woody biomass production potential is estimated to be 230–410 million t annually, and the corresponding total annual power generation potential, at 1 MWh/tons of woody biomass, would be 228–415 TWh (Sudha et al. 2003), equivalent to 36.5–66.5% of total power generated during 2006 (623.3 TWh) in India. Because the photosynthetic efficiency of forest trees, rarely above 0.5%, could be genetically and silviculturally improved to 6.6% (Hooda and Rawat 2006), there is an ample opportunity to improve efficiency up to 1%, thus doubling forest productivity.

Thus, biomass for power generation has a large potential to meet India’s power needs sustainably. The life-cycle cost of bioenergy is economically attractive compared to large coal-based power generation (Ravindranath et al. 2006). Clean biomass, coupled with other changes, could reduce GHG emissions by approximately 640 MT CO$_2$ per year in 2025 (~18% of India’s emissions). Sustainable forestry could increase carbon stock by 237 million Mg C by 2012, whereas commercial forestry could sequester another 78 million Mg Carbon. The sustainable biomass potential of 62–310 million tons per year could provide about 114% of the total electricity generation in 2000 (Bhattacharya et al. 2003).

Sustainable bioenergy potential has also been estimated for Malaysia, Philippines, Sri Lanka, and Thailand (Bhattacharya et al. 2003). Sustainable SRWC production could be 0.4–1.7, 3.7–20.4, 2.0–9.9, and 11.6–106.6 million tons per year, respectively. Using advanced technologies, maximum annual electricity generation may be about 4.5, 79, 254, and 195% of total generation in 2000, respectively. Biomass production cost varies from U.S.$381 to 1842/ha and from U.S.$5.1 to 23 tons.

### 15.2.1.4 Australia

Australia has abundant energy resources, a dispersed population highly dependent on fossil fuel based transport, and relatively fast population growth (Baker et al. 1999). Its total energy consumption has recently increased by 2.6% per year and was estimated to be 4810 PJ in 1997/98. Australia’s per capita GHG emissions ranked third among industrialized countries and were projected to be approximately 552 million Mg CO$_2$-e in 2010, a 43% increase from 1990. In 1995/96, energy production from renewable sources (~263 PJ) was mainly from bagasse (90.3 PJ), residential wood (82.1 PJ), hydroelectric (54.8 PJ), and industrial wood (27.6 PJ).

Its biomass sources including bagasse, paper pulp liquor, forestry and wood processing residues, energy crops, crop residues, and agricultural and food processing wastes may contribute significantly to a 2% renewables target (Baker et al. 1999). Sugarcane, one of the least costly forms of biomass, could alone meet the entire 2% target. Gasification of cotton-gin residues could generate 50 MW of electricity. Rice hulls could support approximately 5 MW of electricity.

The use of SRWCs for bioenergy in Australia is being explored. Interest in the establishment of forest plantations on irrigated and nonirrigated sites in the southern Australia has increased (e.g., Bren et al. 1993, Baker et al. 1994, Stackpole et al. 1995, Baker et al. 1999). Municipal wastewater systems are opportunities for bioenergy production, as land, irrigation infrastructure, and water costs would be part of the total water treatment costs, not part of the costs of biofuel production.

The potential for wastewater-irrigated plantations for bioenergy production is evident in Victoria (Baker et al. 1999). Assuming growth rates of 30 Mg/ha per year, approximately 400,000 Mg per year could generate 50 MW. EG at Wodonga (irrigated with municipal effluent) and Kyabram (first irrigated with freshwater and then groundwater) had growth ranging from 15 to 45 m$^3$/ha per year at 10 years (Baker 1998) when irrigation water salinity and initial soil salinity were not problematic.
At Wodonga, species growth to 4 years was *E. saligna* (134 m$^3$/ha stem volume, 84 Mg/ha above-ground biomass), *EG* (126, 80), *Populus deltoides* × *nigra* (85, 47), *Pinus radiata* (61, 42), *Casuarina cunninghamiana* (43, 49), and *E. camaldulensis* (40, 52) (Stewart et al. 1988). At Kyabram, species ranking at 4 years was *EG*, *E. saligna*, *E. globulus*, and *E. camaldulensis* (Baker 1998).

At Werribee with *E. globulus*, *EG*, *E. saligna*, and *E. camaldulensis* and densities of 1333, 2500, and 4444 trees per ha, stem volume growth to 4 years across planting densities varied: *E. globulus* (57–108 m$^3$/ha), *EG* (46–89), and *E. saligna* (37–77) (Delbridge et al. 1998). Tripling planting density approximately doubled potential yield.

At Bolivar (Boardman et al. 1996, Shaw et al. 1996), initial tree growth rates were relatively high, with species ranking to 4 years of *E. globulus* (139–182 m$^3$/ha overbark stem volume), *C. glauca* (85–111), *E. occidentalis* (90–92), *EG* (75–91), and *E. camaldulensis* (59–71).

A Wagga Wagga project developed national guidelines for sustainable management of water, nutrients, and salt in effluent-irrigated plantations. The project studied biophysical processes under three effluent irrigation rates: medium (M, rate of water use less rainfall), high (H, about 1.5 times M), and low (L, about 0.5 times M). The main species studied were *EG* and *P. radiata*. Tree spacing was 3 × 2 m. Among several conclusions, the project identified best eucalypt species and radiata pine clones for effluent-irrigated plantations for sustainable biomass production, salt sensitivity in tree species, and water use efficiency (Myers et al. 1996). After 6 years, halving irrigation (M vs. L) led to only a 10% decrease in volume production—20 to 18 m$^3$/ha per year.

At Shepparton (Baker et al. 1994), both *E. globulus* and *EG* grew well through 5 years, with *E. globulus* larger than *EG* (172 vs. 128 m$^3$/ha) (Duncan et al. 1999). Stem volume MAIs were 30 and 38 m$^3$/ha for *E. globulus* and 23 and 31 m$^3$/ha for *EG* for 1333 and 2667 trees/ha, respectively. Coppice growth at 2 years varied between 31 and 42 Mg/ha and was greater than that of the planted seedlings. Biomass production for a 12-year cycle of 3-, 6-, and 12-year rotations was projected to be 330, 390, and 350 Mg/ha, respectively, for *E. globulus* growing at an estimated peak of 45 m$^3$/ha per year.

In 1998, Australia had approximately 1.25 million ha of plantations, 23% hardwoods (*E. globulus*, *E. nitens*, *E. regnans*, and *EG*) and 77% softwoods (*Pinus radiata*, *P. elliottii*, *P. caribaea*, *P. pinaster*, and * Araucaria cunninghamii*) (Baker et al. 1999). Although softwood plantations managed in 20–40 year rotations for veneer logs, sawlogs, posts, poles, and pulpwood have bioenergy potential from silvicultural and product residues, the rapidly developing 10–15 year rotation hardwood pulpwood industry also has potential. Australia has a plantation goal of approximately 3 million ha by 2020.

New hardwood plantations in Australia totaled 49,000 ha per year in 1998 and were expected to increase (Baker et al. 1999). These plantations have been mostly for pulpwood on agricultural land in southwestern Western Australia, southeastern South Australia, Victoria, Tasmania, and north-coastal New South Wales. Assuming a growth rate of 20 m$^3$/ha per year and ultimately 500,000 ha, potentially 500,000 Mg per year of wood residue will be available for bioenergy production.

In southern Australia, SRWCs with 3–5 year rotations may be used for bioenergy after alleviating salinization of land and water in dryland (300–600mm annual rainfall) farming systems (Sochacki et al. 2007). Planting density and slope position had strong influences on biomass yield. Mean 3-year yields of *E. globulus*, *E. occidentalis*, and *P. radiata* planted at 500, 1000, 2000, and 4000 trees/ha at upper-, mid-, and lower-slope positions ranged from 12 to 14 tons/ha. Biomass yield consistently increased with planting density, generally greatest at 4000 trees/ha. The best *E. globulus* and *E. occidentalis* yields, 16.6 and 22.2 tons/ha, respectively, were at lower slope positions at 4000 trees/ha, whereas the best yield of *P. radiata* was 15.4 tons/ha in an upper slope position. *E. globulus* did not perform well on the upper-slope site. *E. occidentalis* has some salt tolerance. *P. radiata* yields were relatively low in the lower landscape being relatively small. Using high planting densities and different species for different hydrological settings can optimize biomass productivity. Higher yields are expected under more normal rainfall conditions.

Root:shoot (R:S) ratios that did not vary significantly between planting density and slope position but varied between species (*E. occidentalis*—0.51, *E. globulus*—0.31, *P. radiata*—0.33) have implications for harvesting systems, in terms of biomass yield and stump removal (Sochacki et al.
R:S ratios of 2.5-year-old EG planted at 100–2000 trees/ha decreased with increasing planting density (Eastham and Rose 1990). Roots may be unsuitable for bioenergy because of soil contamination. If roots are not utilized and need to be removed, species with high R:S ratios, e.g., E. occidentalis, may not be desirable.

The whole tree could be harvested and roots removed (Harper et al. 2000). Alternative harvesting scenarios include separation and retention of leaves to maintain site fertility (Sochacki et al. 2007). In the case of root retention in the ground for pasture rather than cereal cropping, P. radiata would be preferred as root decay would allow cereal cropping sooner. Methods to harvest tree crops with roots may be affected by tree size and their respective root systems. Trees grown at 500 trees/ha may be difficult to harvest with typical harvesters (Mitchell et al. 1999).

With high stocking densities and optimal slope position, 3-year biomass yields of 15–22 tons/ha were possible, dependent on species. When averaged across the landscape, yields were more modest and ranged from 12 to 14 tons/ha. These were achieved in lower than normal rainfall conditions; with normal conditions and higher planting densities, higher yields may be possible. To maximize biomass production and water use, planting density, water availability, and species must be matched to site. There are significant opportunities to expand forest bioenergy in Australia through distributed electricity generation and production of ethanol and bio-oil. Utilizing the large amounts of readily available forest residues would generate greenhouse benefits, assist forest regeneration, and improve forest management. New forests in low rainfall environments would also provide residues for energy production, thus enhancing their overall viability. A recent mandate that electricity retailers increase renewable energy production by 9.5 TWh annually has created a small, relatively high value ($10–12/delivered green t) biomass market (Wright 2006).

Producing biochar from farm or forestry waste could have many benefits: generation of renewable electricity, liquid and gas biofuels, activated carbon, eucalyptus oil, heat or low-pressure steam, and a net sequestration of CO$_2$ (McHenry 2009). With new policies and initiatives, the profitability of these various products is likely to improve, especially if integrated into existing agricultural production and energy systems.

Higher rates of soil sequestration and lower uncertainties in carbon asset verification, coupled with lower risks of storing carbon in soils, make integrating biochar applications and agricultural SOC into carbon markets appealing. Carbon markets that include agricultural SOC will enable farmers to trade sequestered biochar soil applications and facilitate expanding new technologies that improve farm productivity and energy security.

Growing SRWCs on surplus and degraded agricultural land could be environmentally beneficial (Bartle et al. 2007). Dryland salinity in southern Australia could be ameliorated using SRWCs. At A$35/green ton and a water use efficiency of 1.8 dry g/kg of water, SRWCs could produce 39 million per year of dry biomass from 1.5% and 8% of farmland in the 300–400 and 400–600 mm rainfall zones, respectively, of the southern Australian wheatbelt.

The relatively low cost of fossil fuels in Australia generally limits the development of bioenergy (Baker et al. 1999). The greatest prospects are therefore crops that yield a commercial product (e.g., eucalypt oil) or provide environmental benefits (beneficial re-use of wastewaters, salinity control in catchments) as well as bioenergy. The economics of bioenergy projects are highly site-specific.

The “Integrated Oil Mallee” project in Western Australia involves more than heat and power generation (Baker et al. 1999; Sims et al. 2006; Bartle et al. 2007). Biomass will come from growing SRWC eucalyptus mallee to help solve the dryland salinity problem on croplands. The mallees are Eucalyptus species (e.g., E. horistes, E. koehii, E. angustissma, E. loxophleba, and E. polybractea) with a multi-stemmed habit, lignotubers, and high oil concentration in their leaves, usually 90% cineole; elite lines have total oil content of 3.2% of leaf fresh weight. Mallee oil has short-term fragrance and pharmaceutical markets and a potential long-term market as a solvent degreaser. By 1999, 12 million oil mallee had been planted on approximately 9000 ha. Linear hedges (twin rows) will be harvested on a 2-year cycle yielding approximately 20 Mg/km FW. Harvesting trees on a 3 to 4 year cycle will provide pharmaceutical oils, activated carbon, heat and power, renewable
energy credits, and even a carbon credit. An Integrated Mallee Processing plant in each mallee
growing area could convert 100,000 Mg per year of mallee (i.e., 50,000 Mg each of leaves and
wood) into approximately (1) *Eucalyptus* oil 1600 Mg, charcoal 8300 Mg, and activated carbon
5000 Mg; (2) electrical energy 2.3 MWh and energy 8.6 MWh; or (3) electrical energy 5.1 MWh,
depending on the conversion process.

A harvester/chipper was developed to produce material suitable for large-volume materials han-
dling systems and low-cost feedstock for oil, charcoal, and thermal energy (Baker et al. 1999). The
machine can harvest and chip mallee stems up to 6 m height and 150 mm basal diameter. The leaf
material is separated from the other material before oil distillation. Although the system is for the
oil mallee industry, it may be applied to any SRWC. Processes and conversion techniques for utiliz-
ing biomass for energy included cogeneration, cofiring, gasification, charcoal, gas, liquids, diges-
tion, and fermentation.

Larger scale plants may follow because the dryland salinity problem extends over millions of
hectares. Direct liquefaction of *eucalyptus* mallee costs less and has higher transportation efficiency
to a central user or processing facility (Bridgwater et al. 2007).

SRWCs and their bioenergy products in the South Australian River Murray Corridor could have
both local and global environmental benefits (Bryan et al. 2008). Some 360,000 ha could produce
over 3 million tons of green biomass annually and reduce annual carbon emissions by over 1.7 million
tons through bioenergy production and reduced coal-based electricity generation. River salinity could
be reduced by 2.65 EC (mS/cm) over 100 years, and over 96,000 highly erosive ha could be stabilized.

Despite these significant opportunities, forest bioenergy has developed little in Australia, except
for firewood for domestic heating. Public acceptance and support are lacking, especially for the use
of natural forest residues, the main biomass source.

### 15.2.1.5 New Zealand

New Zealand has 18 million ha of short rotation hardwoods for multiple use, but only 6.3% of
its energy is obtained from biomass (Wright 2006). Of several *Eucalyptus* species evaluated as
SRWCs, after five 3-year rotations, *E. brookerana* and *E. ovata* were the most productive, achieving
yields as high as 50 dry ton/ha per year (Sims et al. 1999a, 1999b). At an even higher initial planting
density, *E. pseudoglobulus* yielded more after the second 3-year rotation than the top performing
*E. viminalis* clone did in the first (Sims et al. 2001). SRWC genotype selection appears to require
evaluation over several coppice rotations.

### 15.2.1.6 United States

In the United States, which at 103 EJ is the most energy-consumptive country, bioenergy contributes
approximately 2.8%, with approximately 60% of this produced and consumed by the forest products
industry (Wright 2006). Annually, approximately 40% of 250 million dry ton of wood is used for
energy. By 2030, forest bioenergy could double (1.7 EJ) with improvements in forest productivity
and biomass conversion. At present, approximately 50,000 ha of SRWCs are planted in the United
States, with *Eucalyptus* deployed in California, Hawaii, and Florida.

**Hawaii.** An extensive, broad research and development program examined how to grow SRWC
*Eucalyptus* for bioenergy on up to 100,000 ha of former sugarcane land on the island of Hawaii
(Whitesell et al. 1992). Techniques were developed for seedling production and plantation site prepa-
ration, weed control, planting, fertilization, and yield estimation. Tree biomass equations were
derived for EG, *E. saligna*, *Albizia falcata*, *Acacia melanoxylon*, *E. globulus*, *E. robusta*, and
EU (Schubert et al. 1988, Whitesell et al. 1988). Mean annual increment of SRWC *Eucalyptus*
did not peak before significant competition-related mortality, slightly beyond likely harvest age.
Although stand densities of 3364–6727 trees/ha had the highest production, their trees did not reach
the minimum tree diameter, suggesting that yields at lower densities will equal or surpass higher
density yields in longer rotations. To achieve a minimum tree DBH of 15 cm in 5 years, stand den-
sity must be less than 1500 trees/ha.
Certain *Eucalyptus*/*Albizia* mixes appeared promising for maintaining *Eucalyptus* productivity without fertilization. Because *Eucalyptus* yields in 50% and 66% *Albizia* mixes approached that of fertilized pure *Eucalyptus*, and the *Eucalyptus* in mixes were so large, the mixes may be more economical than pure *Eucalyptus* because of lower harvesting costs. The suggested mixed species configuration was alternate rows spaced 3.0 m apart, with *Albizia* planted 2.1 m and *Eucalyptus* 3.0 m apart within their respective rows.

Because efficient harvesting was key to SRWC *Eucalyptus* feasibility, three slightly modified conventional pulpwood harvesting systems were examined. Cable yarding did little damage to the site or stumps but was inefficient because of inexperience and undersized and underpowered equipment. Mechanized equipment, including wheeled and tracked feller-bunchers, a skidder, and a whole tree chipper, handled the trees without difficulty and with relatively inexpensive but damaged stumps. Overall, logistics as well as tree size were major determinants of productivity and cost of harvest. Smaller, less expensive equipment might be more appropriate.

Soil erosion and nutrient depletion with SRWC *Eucalyptus* were minor issues. In spite of high rainfall, pre- and postharvest soil erosion was minimal when a litter layer was developed and retained or when a post-harvest cover crop was used (Schultz 1988). Initial total N levels were inadequate for good growth, presumably because of intensive sugarcane cropping, mineralization and leaching, and depletion of organic matter. N applications were substantially lower than for sugarcane, however. N deficiency could be less when the trees are older because soil N levels after 4 years met or exceeded initial levels, *Eucalyptus* is very efficient at internal recycling of nutrients (Florence 1986), or *Eucalyptus/Albizia* (or other N-fixer) mixes improve N levels and other soil properties. In general, SRWC *Eucalyptus* impacts seem substantially smaller and less frequent than those of agricultural crops, e.g., sugarcane.

Although superior *EG* and *E. saligna* Australian provenances were used, tree improvement would probably increase *Eucalyptus* yields (Skolmen 1986). Short- and long-term improvement programs were proposed but could not be implemented before program termination in 1988. Subsequently, efforts by various public and private agencies have identified promising genotypes in several species.

Costs of production of the three most promising SRWC *Eucalyptus* alternatives were compared. A 5-year rotation on former sugarcane land with periodic fertilization produced the minimum acceptable 15-cm tree at a rate of 20.2 dry ton/ha per year. A 6-year rotation resulted in a 20 cm tree with product quality advantages and a total biomass yield of 18.6 ton/ha per year. An 8-year rotation of *Eucalyptus/Albizia* mix gave a larger tree size at a reduced fertilizer cost, an *Eucalyptus* yield of 22.4 ton/ha per year, and *Eucalyptus/Albizia* yield of 26.9 or more ton/ha per year. Harvesting costs varied with tree size, decreasing by one-third as tree size doubled. Consequently, total costs per dry ton of chipped *Eucalyptus* biomass were highest for the 5-year rotation and lowest for the 6-year rotation. Overall, the information developed by the program provided valuable guidelines for future SRWC *Eucalyptus* ventures in Hawaii.

About 9000 ha of *Eucalyptus* plantations have been established in Hawaii since 1996 (Forest Solutions 2009). Using management procedures from around the world, these plantations are producing over 40 m³/ha per year in the most productive areas.

**Florida.** Because of Florida’s challenging climatic and edaphic conditions, much SRWC emphasis has been placed on *Eucalyptus* tree improvement for adaptability to infertile soils and damaging freezes. U.S. Forest Service research from 1965 to 1984 focused on the best of 67 species for southern Florida (Geary et al. 1983), resulting in >1500 selected *EG* (Meskimen et al. 1987) that were subsequently widely tested to develop four recently released freeze resilient, fast-growing clones. Since 1979, the University of Florida also assessed nine species, producing desirable genotypes of *E. amplifolia* (*EA*) for areas of frequent freezes (Rockwood et al. 1987, 1993). *EG* is now grown commercially in southern Florida for mulchwood (Aaction Mulch 2007) and can be used in central Florida (Rockwood et al. 2008), whereas *EA* is suitable from central Florida into the lower Southeast. *EG* is more productive, largely because of five generations of genetic improvement (Meskimen et al. 1987).
These *EG* and *EA* genotypes are desirable for SRWC systems in Florida and similar regions for many bioenergy applications. On suitable sites and/or with intensive culture, *EG* and *EA* may reach harvestable size in as few as three years (Rockwood 1997, Langholtz et al. 2007). Whole-tree chips of 9-year-old *EG* produced 70% char and oil and 21% noncondensed volatile oil and low-energy gas (Purdy et al. 1978). *EA* and *EG* SRWCs are promising for cofiring in coal-based power plants in central Florida (Segrest et al. 2004), but little is known about their suitability for a wider range of value-added products. Even when used for dendroremediation (Rockwood et al. 1995, 2004, 2005) and windbreaks (Rockwood et al. 2005), *EG* and *EA* may be bioenergy resources.

SRWC opportunities for renewable bioenergy have recently gained momentum in the State’s public policy and in research and media coverage. By combining superior clones (Meskimen et al. 1987, Rockwood 1991), suitable culture (Rockwood et al. 2006, 2008), innovative harvesting (Rockwood et al. 2008), and efficient conversion, *EG* and *EA* are poised to meet bioenergy needs in Florida. As in other SRWC development situations, research and development on genetic material, spacing, fertilization, planting, control of pests and diseases, forest management, etc., will be essential for achieving high SRWC productivity.

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 (Sims et al. 2003). Biomass production and conversion into modern energy carriers must be more fully developed, and favorable policy options such as subsidies and carbon taxes are also needed to support bioenergy expansion.

### 15.2.1.7 Summary

Overall, bioenergy could be the highest contributor to global renewable energy in the short to medium term with SRWC *Eucalyptus* providing a large portion of the biomass (Sims et al. 2006). *Eucalyptus* species can be widely planted to produce abundant biomass (Table 15.3). Several conversion technologies are operational, and more are being developed. Biomass characteristics, difficulty in securing adequate and cost effective supplies early in project development, and planning constraints currently constrain *Eucalyptus* bioenergy development. However, increased biomass productivity and quality, carbon trading, distributed energy systems, multiple high-value products from biorefining, and government incentives should foster *Eucalyptus* use for bioenergy. Opportunities for energy crops include development of biorefineries, carbon sequestration, and small, distributed energy systems.

Many other *Eucalyptus* species may be grown for bioenergy (NAS 1980, 1982). By broad climatic region, these include *E. brassiana*, *E. deglupta*, and *E. pellita* for humid tropics, *E. globulus*, *E. robusta*, and *E. tereticornis* for tropical highlands, and *E. citriodora*, *E. gomphocephala*, *E. microtheca*, and *E. occidentalis* for arid and semiarid regions.

Brazilian experience suggests that *Eucalyptus* bioenergy can be produced sustainably at low cost. With reduced production costs, bioenergy could be commercialized widely and reduce carbon

<table>
<thead>
<tr>
<th>Country</th>
<th>Biomass (EJ)</th>
<th>Biomass (%)</th>
<th>SRWC base (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>7.5</td>
<td>16.4</td>
<td>7–10 million</td>
</tr>
<tr>
<td>United States</td>
<td>2.9</td>
<td>2.8</td>
<td>50,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>2.0</td>
<td>27.2</td>
<td>3 million</td>
</tr>
<tr>
<td>Australia</td>
<td>0.2</td>
<td>3.8</td>
<td>~6000</td>
</tr>
</tbody>
</table>

emissions while enhancing local economies. The Brazilian experience can also be transferred to other developing countries, thus enabling locally produced bioenergy worldwide.

15.2.2 **Eucalyptus Bioenergy Enhancement through Biotechnology and Genomics**

As the main SRWCs in the southern hemisphere, several *Eucalyptus* species have been the subject of studies in genomics and biotechnology, targeted at improving wood and growth properties for bioenergy, or related applications. The most significant developments for enhancement of wood and productivity properties began almost two decades ago, with the production of the first dense genetic maps. Before that, the available tools were severely restricted to the analysis of few genetic loci. Since then, most research efforts in *Eucalyptus* genomics have been dedicated to the discovery of polymorphisms that confer superior phenotype to elite trees. The expectation is that these polymorphisms identify genetic markers for indirect selection in breeding programs, but may also define a gene for modification using transgenic approaches.

As a first step in the establishment of the tools necessary to identify genes of economic value for selection, the first high-density *Eucalyptus* genetic maps were established in the mid-1990’s (Grattapaglia and Sederoff 1994). Development of genetic maps was soon followed by the mapping of genomic regions, of quantitative trait loci (QTL) that regulate a portion of the phenotypic variation for wood quality and growth (Grattapaglia et al. 1995, 1996). These early developments were highly restricted because of the lack of sequence information for *Eucalyptus*, and most other woody species. This deficiency started to diminish in the past decade, initially with the high-throughput sequencing of fragments of expressed genes (expressed sequence tags, or ESTs) (Paux et al. 2004; Vicentini et al. 2005; Novaes et al. 2008), and more recently with the perspective of the availability of the first *Eucalyptus* genome. Here we review the developments in the use of biotechnology and genomics, aimed at improving bioenergy traits in *Eucalyptus*. For general reviews about *Eucalyptus* genomics and its applications to breeding, the readers are directed to other recent publications (Poke et al. 2005; Myburg et al. 2007; Grattapaglia and Kirst 2008).

15.2.2.1 Genetic Mapping and Quantitative Traits Loci Analysis

Most mapping studies in agricultural crops or model plants have relied on the analysis of inbred lines, near-isogenic lines or backcross progenies. In outbred tree species like *Eucalyptus*, the long-generation time and high genetic load have limited the development of these types of segregating populations (Kirst et al. 2004a). To address these limitations, new mapping strategies that use half-sib, full-sib and pseudo-backcross populations were developed and successfully implemented (Grattapaglia and Sederoff 1994; Myburg et al. 2003). Isozyme markers were first applied to genetic mapping of *Eucalyptus* (Moran and Bell 1983) but were of limited use for genetic studies that require high-density, saturated maps. Restriction fragment polymorphism markers were also used for the development of second-generation genetic maps (Byrne et al. 1995; Thamarus et al. 2002). However, the most significant advances came with the development of PCR-based markers such as random amplified polymorphic DNA (RAPD) markers (Grattapaglia and Sederoff 1994; Verhaegen and Plomion 1996; Bundock et al. 2000; Gan et al. 2003), amplified fragments length polymorphism (AFLP) and microsatellite markers (Brondani et al. 1998, 2002; Marques et al. 1998, 2002; Bundock et al. 2000; Gion et al. 2000; Thamarus et al. 2002; Gibbs et al. 2003). A few genes have also been added to existing maps (Bundock et al. 2000; Gion et al. 2000; Thamarus et al. 2002).

Development of high-coverage genetic maps established the foundation for the quantitative genetic analysis of bioenergy traits in *Eucalyptus* and identification of genes that regulate them. QTL analyses for traits associated with biomass growth have been numerous in *Eucalyptus*, including in pure *EG* crosses (Grattapaglia et al. 1996), *E. nitens* (Byrne et al. 1997), *EG* and *EU* hybrids (Verhaegen et al. 1997) and *EG* and *E. globulus* crosses (Kirst et al. 2004b). The first report (Grattapaglia et al. 1996) identified three QTL, explaining 13.7% of the phenotypic variation for
circumference at breast height in a large half-sib population of *EG*. Similarly, other studies have also typically reported few QTL with moderate to high effect in growth and biomass traits, suggesting an immediate value of this information for marker-assisted selection. QTL analysis of chemical and physical property traits (e.g., lignin and cellulose content, wood specific gravity), which are critical for efficient biomass conversion to biofuels, was initially severely hampered by the cost, labor and time required for sample analysis. However, the development of novel methods for high-throughput phenotyping, such as near-infrared spectrometry, SilviScan (x-ray densitometry combined with automated scanning x-ray diffraction and image analysis) and mass spectrometry, computer tomography x-ray densitometry (CT scan) and pyrolysis molecular beam mass spectrometry (pyMBMS) has modified that scenario drastically in the past decade, and analysis of these traits is now commonplace. For example, the application of indirect, high throughput phenotyping of wood quality traits by NIR was demonstrated in *Eucalyptus*, and the information used for QTL mapping in a pseudo-backcross of *EG* and *E. globulus* (Myburg 2001). Approximately 300 individuals that had been previously genotyped with AFLP markers were analyzed by NIR, and predictions were made for pulp yield, alkali consumption, basic density, fiber length and coarseness, and several wood chemical properties (lignin, cellulose and extractives).

In summary, efforts to identify regions of the genome that regulate biomass growth and wood quality in *Eucalyptus* have been largely successful. However, the use of this information in breeding programs was rapidly shown to be unreliable because of two main factors: (1) rapid linkage disequilibrium (LD) decay among unrelated individuals and (2) the extensive level of genetic heterogeneity in diverse populations, as previously predicted (Strauss et al. 1992). The low extent of LD meant that significant marker-trait associations detected in specific segregating populations were not detectable when unrelated genotypes were considered. The genetic heterogeneity of existing populations, where multiple alleles at a large number of loci may contribute to trait variation, signified that marker-trait associations detected in one pedigree were not relevant in all backgrounds. Therefore, it became clear that the identification of makers associated with traits in one or few segregating populations was not sufficient, but that the causative polymorphisms, or at least knowledge of the specific gene that regulated trait variation, was necessary. However, success in positionally cloning QTL in forest tree species (Stirling et al. 2001), as it had been done in some agricultural crops like tomato (Paterson et al. 1988; Martin et al. 1993), was not immediately achieved.

### 15.2.2.2 Genomics and the Identification of Genes Regulating Bioenergy Traits

Identification of genes that regulate quantitative variation in plants, animals and humans, went through significant advances in large part because of the development of genomic technologies. The high-throughput sequencing of expressed genes initiated in the beginning of the decade, with the release of the first ESTs of *Eucalyptus* species (Kirst et al. 2004b). This initial effort was rapidly followed by more extensive EST sequencing projects, which surveyed the pool of genes expressed in several *Eucalyptus* tissues, and identified putative orthologs for the suite of genes involved in metabolic and regulatory pathways associated with biomass growth and wood quality (Kirst et al. 2004b). The sequencing of expressed genes lead to the development of the first studies that characterized the expression of large number of genes (i.e., transcriptomics) in *Eucalyptus* and hybrid populations (Voiblet et al. 2001; Kirst et al. 2004b). A genetic genomics study, which combined the information from QTL of biomass growth and sequence and expression of genes in differentiating xylem suggested that the genetic elements that regulated traits related to bioenergy and other properties could be rapidly unraveled (Kirst et al. 2004b, 2005). Similarly, novel approaches to identify polymorphisms that regulate complex traits were also developing rapidly in *Eucalyptus*. Thumma and colleagues were the first to demonstrate the power of association genetics in a tree species (Thumma et al. 2005), which relies on the detection of polymorphisms associated with quantitative variation in populations of unknown ancestry, in a woody species. Specifically, the study identified cinnamoyl CoA-reductase (CCR), a known gene in the phenylpropanoid pathway, as being a significant determinant of fiber properties in *Eucalyptus*. Although this first study was focused on
a specific gene, several studies are underway that explore the identification of genes of value for bioenergy for several hundred genes, targeting particularly those that code for enzymes of the lignin and carbohydrate/cellulose pathways.

### 15.2.2.3 Future Developments

Biotechnology and genomics research have allowed for achievements in the past few years that were inconceivable at the beginning of the millennium. Procedures for genome sequencing, as well as transcriptome, proteome, and metabolome characterization have all gained in efficiency by two to three orders of magnitude within less than a decade. At the same time, the costs per data point have been reduced by the same proportion. As a consequence of the decrease in cost, and the growing interest of the U.S. Department of Energy (DOE) in bioenergy crops, an *Eucalyptus* genotype was selected recently for sequencing by the Joint Genome Institute (JGI)/DOE, for completion in early 2010. The sequence will provide the foundation on which QTL cloning should become achievable. The genome sequencing and the complete catalogue of genes will also allow for the development of genomic tools such as whole-transcriptome microarrays, for characterization of gene expression variation. The current sequence has coverage of $4 \times$ (meaning that, on average, every nucleotide has been sequenced 4 times) and is expected to reach $8 \times$ by the summer of 2009. An assembly based on the existing sequence data has already captured almost 80% of the genome sequence. This suggests that—with the added sequencing to complete $8 \times$—the final genome information will be close to completion. The individual being sequenced is an elite *EG* genotype (Brasuz1). To support the assembly and annotation of the genome sequence, two bacterial artificial chromosomes (BACs) have been developed and over one hundred thousand BAC-ends have been sequenced. Furthermore, a number of pedigrees are being genotyped with diversity array technology (DArT), microsatellite, gene expression (GEM) and single-feature polymorphisms (SFP) markers, for the development of hyper-saturated genetic maps that will be invaluable for the sequence assembly. To support the annotation of the genome sequence (i.e., identification and definition of function for genes in the genome), JGI is also sequencing a large number of random gene sequence fragments (expressed sequence tags).

Perhaps even more exciting are the anticipated developments in the years ahead, particularly in genome sequencing. Platforms in development have recently demonstrated the capacity to generate sequencing data—although not yet fully interpretable—over 10–20 kilobases within a few hours (Korlach et al. 2008). At the same time, miniaturization of devices and single molecule detection methods now permit sequencing of several million molecules in parallel (Eid et al. 2009). In that scenario, sequencing a moderate size genome such as *Eucalyptus* (~500–600 Mbp) could be achieved in less than one day. Ultra low sequencing reaction volumes also suggest that the costs of such a task will be a few hundred U.S. dollars, rather than the current several hundred thousand.

In summary, in the next decade, genetic and genomics studies will likely discover the majority of genes that regulate a significant part of the heritable variation of biomass productivity and wood property traits in *Eucalyptus* and the most commercially important tree crops, such as *Populus* and *Pinus*. Consequently, it will be possible to identify superior genotypes based in large part on their genotype across multiple critical loci. The challenge will be to develop genotyping assay methods that will be sufficiently cost effective to permit rapid screening of large progenies in breeding programs. That will allow the development of genotypes that combine the optimal alleles for each specific end-use purpose, including plants optimized for bioenergy purposes.

### 15.3 PINE

Worldwide, *Pinus* species are currently widely used for bioenergy and have considerable potential for future use. The *Pinus* genus has over 100 species (Syring et al. 2005), and pines have high genetic and phenotypic diversity that has bioenergy ramifications. Many pine species growing in natural stands and/or established in plantations provide bioenergy opportunities.
In the United States, the forest products industry is currently the largest producer of bioenergy, much of which is in the southeastern United States. The approximately 82 million ha of forestland in the Southeast produce 18% and 25% of the world’s roundwood and pulp, respectively (FAO 2004). Loblolly, *P. taeda*, and slash, *P. elliottii*, are the most important southern pines because of their broad natural ranges that constitute the majority of the approximately 15 million ha of plantations in the Southeast (Peter 2008). The main products for loblolly and slash pine plantations have been pulpwod, wood composites, sawtimber, and poles/pilings. Loblolly pine and slash pine are in closely related clades (Dvorak et al. 2000). Loblolly pine is a model pine because of its economic importance and well characterized reproduction and genetics (Lev-Yadun and Sederoff 2000).

Silvicultural intensity for loblolly and slash pines varies depending on plantation objectives and initial investments. Silvicultural treatments and genetic improvement greatly enhance tree growth and stand productivity (Fox et al. 2004, 2007) and shorten rotations. Seed orchards provide >95% of the seed for commercial nurseries, and aggressive breeding and genetic testing are underway.

Tree improvement has focused on growth, stem form, and disease resistance. Improving volume growth and yield has been emphasized (White et al. 1993, McKeand and Bridgwater 1998). In the first two breeding cycles of loblolly pine, gains of 30–40% in stem volume per cycle were achieved (Li et al. 1999). Resistance to fusiform rust and pitch canker may also be improved in loblolly and slash pines (Kayihan et al. 2005). Loblolly and slash pines each have only one breeding zone each because genetic by environmental interactions are not significant (McKeand et al. 2006). Southern pines can be clonally propagated by rooted cuttings and somatic embryogenesis (Nehra et al. 2005). Varietal lines of elite germplasm selected and propagated by somatic embryogenesis have been developed, and loblolly pine varieties are now being commercially deployed in the Southeast.

Although wood properties are important in the traditional utilization of southern pines (Peter 2007; Peter et al. 2007) and presumably also for bioenergy, improvement programs are not actively breeding for these traits. Wood density is under moderate to high heritability in loblolly and slash pines. Strong correlations between juvenile and mature wood suggest that early selection can be used. In loblolly pine, it may be more difficult to improve both density and growth simultaneously. Significantly less is known about genetic control of wood chemical composition in loblolly and slash pines, even though these traits are significant for both chemical pulp production and bioconversion to ethanol. Loblolly pine wood chemical composition is under weak genetic control in juvenile and mature wood, and was not correlated, or only weakly so, with growth (Sykes et al. 2006).

Loblolly pine’s economic importance, genetic material, and easily studied wood characteristics have stimulated significant biotechnology research, e.g., Sewell et al. (1999, 2000, 2002), Brown et al. (2004), Kirst et al. (2003), and Lorenz et al. (2006). A large loblolly pine resequencing project discovered single nucleotide polymorphisms (SNP) in 8000 unigenes (Neale 2007), which will identify gene candidates that control disease resistance and wood properties, potentially leading to a genome sequence. Genetic engineering methods can genetically transform loblolly pine. Transgenic plants have been derived from an organogenic method starting with mature zygotic embryos (Tang et al. 2001) and from somatic embryos (Connett-Porceddu and Gulledge 2005).

Advanced generation southern pines in the Southeast have high bioenergy potential (Peter 2007). Tree improvement programs and management systems coupled with clonal propagation, genetic engineering, and genomic research customizing trees for bioenergy and chemicals make southern pine even more promising for bioenergy production through (1) integrated forest biorefineries that produce bioenergy and biofuels in addition to pulp and paper (Van Heiningen 2006; Chambost et al. 2007a, 2007b; Towers et al. 2007) or (2) co-firing, wood pellets, biofuels, or gasification. Overall, harvesting and transportation account for approximately two-thirds of the total delivered wood costs (Peter et al. 2007).

Although harvesting and transporting small diameter trees is a significant cost barrier to growing and using southern pines for bioenergy, slash and sand (*P. clausa*) pines have been evaluated as SRWCs with more than 4000 trees/ha and harvests within 8 years (Campbell 1983; Campbell et al. 1983; Frampton and Rockwood 1983; Rockwood et al. 1983, 1985; Rockwood and Dippon 1989).
Yields from high-density slash pine stands peaked at 9800 trees/ha at 80 mt/ha at age 6 years and 98 mt/ha at 10 years at 6200 trees/ha (Campbell 1983; Campbell et al. 1983). Through three years on a site with a higher P level, slash pine yields nearly tripled when stand densities tripled even up to 43,300 trees/ha, but on a less fertile site, a similar tripling of yield only extended up to 14,600 trees/ha (Rockwood et al. 1983). High density sand pine appeared less productive and required longer rotations, with maximum yields up to 8 mt/ha per year at almost 20 years. In spite of favorable energy output/input ratios of as high as 28 and 26 for slash and sand pine SRWCs with 5–20 year rotations, respectively, only slash pine SRWC systems generated suitable break-even prices (Rockwood et al. 1985). Although biomass yields from these early SRWC tests were low, genetic variation within slash and sand pines for traits including survival and tree biomass quantity and quality may be utilized to increase their SRWC productivity (Frampton and Rockwood 1983). Still, because southern pines do not coppice, they are not well suited to SRWC systems.

Combustion, pyrolysis, gasification, and bioconversion convert wood into heat, electricity and liquid fuel (Peter 2007). The well-established infrastructure and extensive plantations in the forest products industry are huge advantages for using southern pine for bioenergy. European demand for renewable sources of electricity is driving wood pellet production using southern pine roundwood (Kotra 2007), and the U.S. forest products industry is actively researching integrated forest biorefineries (Amidon 2006; Larson et al. 2006; Van Heiningen 2006; Chambost et al. 2007a, 2007b; Towers et al. 2007).

Wood gasification facilities to convert wood into energy and power are planned in the Southeast. For example, a northern Florida facility to produce electricity and gas began construction in 2008. Also in 2008, a facility to produce ethanol from syngas was begun in south Georgia. Oglethorpe Power Corporation (OPC), the United States’ largest power supply cooperative, is planning to build as many as three 100 MW biomass-fired electric generating facilities in Georgia. The facilities will provide power to OPC’s members, which supply electricity to nearly 50% of Georgia’s population. The steam-electric power plants will use fluidized bed boiler/steam turbine technology for a woody biomass mixture.

Other pine species elsewhere in the world that exemplify additional bioenergy opportunities from natural stands and plantations include radiata pine (P. radiata), jack pine (P. banksiana), and P. halepensis. Radiata pine is widely planted as an exotic in New Zealand, Chile, and other temperate regions. Jack pine is a wide ranging species in northern North America. P. halepensis is common to semiarid Mediterranean areas.

Renewable energy, particularly bioenergy, can be important for reducing New Zealand’s greenhouse gas emissions back to 1990 levels by 2012 (Hall et al. 2001). Currently, biomass provides less than 5% (28 PJ) of New Zealand’s primary energy supply. However, large quantities of current and future forest residues have potential to fuel biomass power generation. New Zealand has approximately 1.7 million ha of forest plantations of which 91% is P. radiata. By 2010, the annual log harvest is expected to be over 30 million m³. Residue delivery costs largely depended on the delivery system chosen, the site characteristics and the transport distance. The cheapest system ranged from 22 to 37 NZ$/ton (1.2–2.0 NZ$/GJ) for residues at the landing and from 29 to 42 NZ$/ton (1.6–2.2 NZ$/GJ) for residues collected from the cutover. The cheapest option was the simplest system because extra handling added cost. Use of landing residues for the generation of heat and/or electricity could be feasible, particularly for sites with short transport distances on private roads that have no legal restrictions for payloads. Biomass delivery systems have also been assessed elsewhere for forest residues (Bjorheden 2000), willow short rotation coppice (Gigler et al. 1999), and biomass fuel mixes (Allen et al. 1997; Sims and Culshaw 1998).

Potential forest bioenergy costs in central Chile were estimated (Faundez 2003), as approximately 70% of Chile’s energy comes from imported fossil fuels, and approximately 70% of its electricity comes from hydroelectricity. Biomass does contribute 19% of the total energy (mainly as firewood from native forests), but increasing its share would have economic and environmental benefits. Sustainable production of firewood would reduce the use of native forests.
The potential production costs of four silvicultural regimes for *Populus*, *Salix*, *Pinus*, and *Eucalyptus* considered the costs of cultivation, harvest, and soil use, yields expected at each site, and the energy value of biomass (Faundez 2003). *Populus* and *Salix* grow quickly and have been widely used for bioenergy, whereas *Pinus* and *Eucalyptus* plantations occupy >2 million ha in central Chile. Because of a nonlinear relationship between soil use cost and productivity, the minimum costs for both nonintensive *Pinus* and *Eucalyptus* regimes were for high productivity sites (more expensive land), whereas for both intensive *Populus* and *Salix* regimes, the minimum costs were for low productivity sites (less expensive land). Minimum costs of production of the nonintensive regimes of 0.0355–0.1662 UF/GJ for *Eucalyptus* and 0.0626–0.3822 UF/GJ for *Pinus* were at most one-half those of the intensive regimes of 0.1201–0.1325 UF/GJ for *Populus* and 0.1387–0.1503 UF/GJ for *Salix*, which were fairly insensitive to site productivity.

Given the large area of land available in central Chile for nonintensive compared to intensive forestry and the broad experience with nonintensive *Pinus* and *Eucalyptus*, these regimes appear best (Faundez 2003). Because their energy production costs were comparable to those for oil and natural gas, forest bioenergy could be a feasible alternative to fossil fuels and a way to avoid CO2 emissions. If forests are to be used for bioenergy in Chile, selection of appropriate clones and species will be essential for increasing productivity.

Jack pine SRWC production in Wisconsin peaked at age 5 in the densest planting and progressively later in more open spacings (Zavitkovski and Dawson 1978). Biomass production was two or more times higher than in plantations grown under traditional silvicultural systems. For 10-year-old irrigated, intensively cultured plantations in northern Wisconsin, energy inputs (site preparation, fertilization, weed control, irrigation, harvesting, chipping, and drying) were approximately 20% of the total energy (Zavitkovski 1979). The net energy of 1863 MBtu/ha, equivalent to 340 barrels of oil, was 13% more energy than reported for highly productive, nonirrigated, intensively cultured stands in eastern United States. Net energy returns were linearly and positively correlated with energy invested in both irrigated and nonirrigated, intensively cultured plantations and a naturally regenerated forest, indicating that intensive culture brings commensurate returns.

In association with fire hazard reduction policies, forest biomass from extensive natural pine forests, such as in northern California, southwestern Oregon, and Oregon east of the Cascade Mountains, can fuel power plants (Barbour et al. 2008). For three hazard reduction scenarios, the mix of species and sizes removed was similar, and average yields were quite high. Sawlogs were 67 to 79% of the weight removed. Tops and limbs of commercial species >25.4 cm DBH and noncommercial species provided most of the biomass chips. Low value conifers (17.8 to 40.6 cm DBH) were also an important biomass source, whereas trees <17.8 cm DBH were a relatively minor component. To pay for fire hazard reduction treatments, 9.1 to 18.2 mt/ha of sawlogs plus perhaps a quarter of that in biomass chips need to be removed. Considerable emphasis has been placed on finding uses for small trees (USDA FS 2005; USDE and USDA 2005). Fire hazard reduction treatments could provide enough raw materials to fuel one or more 20 MW wood-fired electrical power generation plants.

In arid and semiarid Mediterranean regions, *P. halepensis* and other pines are potential bioenergy sources. For example, Catalonia in northeast Spain has 12,146 km² of forests (38% of Catalonia, 10% of Spain’s forests) composed primarily of *Quercus ilex*, *P. sylvestris*, *P. halepensis* and *P. nigra* (Puy et al. 2008). The Catalan Energy Plan 2006–2015 estimates 197% more forest and agricultural biomass consumption, mainly as heating for household and industrial uses, such as sawmills. Catalonia’s biomass potential of forest, agricultural, and sawmill residues, and other bulky wastes is approximately 2.6 million tons, approximately 1 Mtoe. If forest biomass is to be an important bioenergy source in Mediterranean countries, key factors are property regimes, low productivity, weak institutional capacity, logistics and supply difficulties, and forest product profitability. Technological solutions alone do not guarantee a prominent role for forest biomass in southern Europe.
15.4 POPLAR BIOENERGY USE AND POTENTIAL WORLDWIDE

15.4.1 INTRODUCTION AND BACKGROUND

The use of poplars for bioenergy is not new (Anderson et al. 1983; Dickmann and Stuart 1983; Dickmann 2006). In fact, there is archaeological and historical evidence that poplars have been used for cooking and fuel throughout civilization. For example, archaeological evidence suggests that indigenous people in North America including the Paleo-Indian, Hohokam and Ojibwe used poplar for cooking and heating as well as many other uses as early as 3000 BC (Logan 2002). Over a thousand years ago Euphrates poplars growing along the Tigris and Euphrates rivers, now in Iraq, were used for charcoal and many other practical uses by the third Dynasty of Ur in Mesopotamia (Gordon 2001). Moreover, the ancient Chinese before the Han Dynasty also used poplars for cooking and heating at Youmulakekum in Western China from 700 to 200 BC; and during the Xian period in China there is archaeological evidence that poplars were used for fuel and other practical uses around 600 AD (Zhang J, personal communication).

Poplars have been used for fuel since antiquity throughout Europe, the Middle East, near East, and Mediterranean in close association with agriculture (Zsuffa 1993). And, according to the diaries of Lewis and Clark and David Thompson in the early 19th century, the native cottonwood growing along the rivers was used for cooking and fuel during the exploration and settlement of the western United States and Canada (DeVoto 1953; Richardson et al. 2007).

Thus, it is well documented that poplar has been a source of bioenergy throughout early civilization. However, as the world became industrialized, both industry and home owners became dependent upon inexpensive fossil fuels for energy, and the use of wood for fuel declined. But, in the early 1970s when fossil fuels became more expensive and scarce, modern societies began to seek alternative sources of energy such as biomass (Rockwood et al. 2004). Over the years, the forest products and pulp and paper industries have been the largest user of poplar biomass for energy in developed industrialized countries; in fact, now they have largely become energy self-sufficient through their use of biomass as a fuel (Konig and Skog 1987).

The aforementioned oil crisis and shortages in the 1970s sparked a worldwide emphasis on bioenergy research and development from trees, especially poplar (Fege et al. 1979; Ranney et al. 1987). But, after only a few years when fossil fuels became more available and inexpensive again, bioenergy research and development on poplars declined. Recent oil shortages and increased costs of fossil fuels in the 21st century have prompted yet another new wave of emphasis on alternative fuels and bioenergy from poplar biomass.

Poplars have received worldwide attention for bioenergy use because of their high biomass production rates and genetic improvement potential (Stettler et al. 1996; Davis 2008). We review worldwide poplar biomass production rates and discuss the advantages and limitations of using poplars for bioenergy, with emphasis on the current and potential future use of poplars for bioenergy in developed countries. We fully realize that poplar is still an important source for fuel for cooking and heating in many developing countries, and will likely remain so for years to come (FAO 2009).

15.4.2 POPLAR BIOMASS PRODUCTION

15.4.2.1 North America

The origin of the use of poplar plantations for biomass production in North America dates back to the late 1800s and early 1900s when governmental agencies became concerned that the forests of the northeastern United States and Canada were not sustainable because of overharvesting (McKnight and Bisterfeldt 1968). This concern led to the establishment of the U.S. Forest Service in 1905 and the Forest Survey in 1928 (LaBau et al. 2007). At the same time, Stout et al. (1927) working at the New York Botanical Garden outlined opportunities for meeting the growing needs
for wood through poplar tree breeding. Stout and Schreiner (1933) reported on their pioneering breeding effort in hybridizing poplars that was patterned after the classical work of A. Henry in the United Kingdom (Henry 1914). Also, in the 1920s and 1930s Canadian poplar breeder pioneers Frank Skinner and Carl Heimburger began their pioneering poplar breeding programs in Canada (Richardson et al. 2007). These four pioneering tree breeders laid the foundation for the next 100 years of poplar breeding for biomass production in North America.

In the United States from 1900 to the 1940s, poplar plantations were mostly made up of native poplar species, including eastern cottonwood (*Populus deltoides*) and black cottonwood (*P. trichocarpa*) (Bearce 1918; McKnight and Biesterfeldt 1968; Smith and DeBell 1973). In Canada during that same period, there were thousands of hectares of abandoned farm land planted to native poplars and imported hybrid poplars from Europe (Smith 1968). These plantations had varying degrees of success depending upon conditions (Smith and Blom 1966). There were also thousands of hectares of both native poplars and hybrids planted in shelterbelts and windbreaks during early settlement of the Canadian and American west (Cram 1960).

Initially, these poplars were grown for shelter, but they were also used for fuelwood and other wood products (Richardson et al. 2007). The multitude of hybrid poplars developed by Stout and Schreiner (1933) were tested throughout North America during the 1930s and 1940s to determine their adaptability to varying conditions including survival, growth, as well as pest and disease resistance. These hybrids, known as Oxford Paper (OP) or Northeast (NE), showed varying degrees of growth and survival largely because of climatic factors, cultural practices, and disease susceptibility (Blow 1948; Smith and Blom 1966; Maisenhelder 1970).

In the 1950s, Ernst Schreiner, then with the U.S. Forest Service, distributed the better performing NE hybrid poplars to cooperating landowners throughout North America to gain information on their performance. He also shared the NE hybrid poplar clones with many other countries so they might be tested under worldwide conditions (Garrett 1976). Many of them did not live up to their expectations in Canada, Europe, and Eurasia (Pryor and Willing 1965; FAO 1980). Canadian poplar breeders in the meantime were developing their own poplar hybrids for use in Canada (Smith 1968; Richardson et al. 2007). Moreover, an active program of selection and breeding of eastern cottonwood was initiated in the eastern and southern United States in the late 1950s and 1960s (Wilcox and Farmer 1967; Schreiner 1971). These breeding programs focused on improving adaptability, growth and disease resistance with primary emphasis on producing wood for sawtimber and pulp and paper (Thielges and Land 1976).

In the 1960s, there was a change in the focus on sawtimber and pulp and paper to biomass of the forest. This change was largely due to the efforts of production ecologists interested in determining the primary production of the vegetation of forests including dry matter production and energy accumulation. An initiative was known as the National Academy of Science, International Biological Program (IBP) had one of their focal points on production of the eastern deciduous forest biome (Newbould 1967). This program resulted in a number of studies of the standing crop biomass and caloric values of native poplar stands and plantations (Peterson et al. 1970; Switzer et al. 1976; Zavitkovski 1976; Crow 1978). The change in emphasis to weight of forest products rather than volume prompted the U.S. Forest Service to start tallying biomass beginning in 1964 (LaBau et al. 2007). Also, there was recognition by many that intensive forest utilization required an understanding of functional forest ecosystem processes, including dry matter, energy and chemicals (Young 1973). Moreover, biomass studies were essential to realizing the full potential of the forest for energy (Young 1971, 1973, 1976, 1977).

The concept of short rotation forestry or short rotation woody corps developed in parallel with the biomass and bioenergy studies of forests (Larson and Gordon 1969; Gordon 1975). Schreiner (1970) called it “mini-rotation forestry.” Short rotation forestry involves growing trees on short rotations (i.e., <15 years) using agronomic principles including planting genetically improved stock, fertilization, irrigation, weed and pest control (Drew et al. 1987; Dickmann 2006). Early efforts to identify suitable species for short rotation forestry included many species (Dawson 1976), but
after many field trials Populus emerged as one of the top candidates for further research. Poplars emerged because they are genetically diverse, amenable to genetic improvement, fast growing, easy to propagate and well-studied (Dickmann et al. 2001). A key factor in the acceleration of research on poplars for bioenergy was the OPEC oil embargo of 1973. Soon after the huge increase in oil prices, the oil importing countries began seeking alternative sources of energy including biomass (Dickmann 2006). Research and development efforts were soon initiated on bioenergy by many governmental agencies. For example, the International Energy Agency (IEA) was formed to foster international research and development on energy in 1974. IEA includes a Bioenergy Task 30—Short Rotation Crops for Bioenergy Systems. In 1978, the U.S. Department of Energy (DOE) initiated a Short Rotation Woody Crops Program, which was later was renamed the Biofuels Feedstock Development Program. This program provided funds for poplar cultivation, genetics, physiology, pest management, growth and yield for 25 years. This continuous source of funding provided the research continuity needed to advance poplar bioenergy research significantly (Stettler et al. 1992). Similar bioenergy funding for poplars became available in the Canadian Forest Service and Energy Agency. In 1995 the USDA Forest Service, the U.S. DOE, and the Electric Power Research Institute (EPRI) also established the Short Rotation Woody Crop Operations Working Group to pursue efficient development of practices of culture, harvest and handling of woody biomass plantations. Further details of the history of poplar production and bioenergy in the United States and Canada are provided by Thielges and Land (1976), Dickmann (2006) and Richardson et al. (2007).

Published data on biomass production rates in North America range from 2 to 35 mt/ha per year (Table 15.4). Realistic yields are probably in the range of 5–20 mt/ha per year (Stanturf et al. 2001; Dickmann 2006; Davis 2008). The reasons for the large variation are many. Some reports were from small plot experiments and unreplicated demonstrations whereas others are from larger replicated field studies, or genetic trials with adequate border rows, or plots within commercial operational

### TABLE 15.4

**Chronological Synthesis of Poplar Biomass Production Field Studies and Plantations by Location in North America**

<table>
<thead>
<tr>
<th>Location</th>
<th>Clone/Species*</th>
<th>Age (years)</th>
<th>Spacing (m)</th>
<th>Productivity (mt/ha per year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>W US</td>
<td>T</td>
<td>2</td>
<td>0.3</td>
<td>13.4–20.9</td>
<td>Heilman et al. (1972)</td>
</tr>
<tr>
<td>W US/Canada</td>
<td>T</td>
<td>Multiple</td>
<td>0.3–1.2</td>
<td>9.0–11</td>
<td>Smith and DeBell (1973)</td>
</tr>
<tr>
<td>S US</td>
<td>D</td>
<td>5–20</td>
<td>3.0</td>
<td>10–11</td>
<td>Switzer et al. (1976)</td>
</tr>
<tr>
<td>NE US</td>
<td>DN</td>
<td>4</td>
<td>0.12–0.76</td>
<td>7.7</td>
<td>Bowersox and Ward (1976)</td>
</tr>
<tr>
<td>NC US</td>
<td>DN</td>
<td>4</td>
<td>0.23–0.61</td>
<td>11.3–13.8</td>
<td>Ek and Dawson (1976)</td>
</tr>
<tr>
<td>E Canada</td>
<td>DN</td>
<td>Multiple</td>
<td>Multiple</td>
<td>5–19</td>
<td>Anderson (1979)</td>
</tr>
<tr>
<td>W US</td>
<td>T</td>
<td>8</td>
<td>0.3–1.2</td>
<td>5.8–9.7</td>
<td>Heilman and Peabody (1981)</td>
</tr>
<tr>
<td>NC US</td>
<td>B</td>
<td>5</td>
<td>1.2</td>
<td>4.2</td>
<td>Isebrands et al. (1982)</td>
</tr>
<tr>
<td>W US</td>
<td>T,TD</td>
<td>4</td>
<td>1.2</td>
<td>5.2–27.8</td>
<td>Heilman and Stettler (1985)</td>
</tr>
<tr>
<td>W US</td>
<td>T,TD</td>
<td>4</td>
<td>1.2</td>
<td>11.3–12.6</td>
<td>Heilman and Stettler (1990)</td>
</tr>
<tr>
<td>NC US</td>
<td>DN,B</td>
<td>Multiple</td>
<td>Multiple</td>
<td>4.9–12.8</td>
<td>Strong and Hansen (1993)</td>
</tr>
<tr>
<td>W US</td>
<td>TD</td>
<td>5</td>
<td>0.18–0.3</td>
<td>6.4–30</td>
<td>DeBell et al. (1993)</td>
</tr>
<tr>
<td>W US</td>
<td>TD</td>
<td>7</td>
<td>0.5–2.0</td>
<td>10.1–18.2</td>
<td>DeBell et al. (1996)</td>
</tr>
<tr>
<td>W US</td>
<td>T,TD</td>
<td>7</td>
<td>1.0</td>
<td>11–18</td>
<td>DeBell et al. (1997)</td>
</tr>
<tr>
<td>W US</td>
<td>T,TD</td>
<td>4</td>
<td>1.0</td>
<td>14–35</td>
<td>Scarascia et al. (1999)</td>
</tr>
<tr>
<td>NC US</td>
<td>DN</td>
<td>7–12</td>
<td>2.4</td>
<td>4.7–10</td>
<td>Netzer et al. (2002)</td>
</tr>
</tbody>
</table>

* B, *P. balsamifera*; D, *P. deltoides*; N, *P. nigra*, T, *P. trichocarpa*; DN, D × N; TD, T × D; N, north; E, east; S, south; W, west; C, central; US, United States.
plantings. Yield data from small plots are higher than larger ones because of an edge effect bias (Zavitkovski 1981). The yields across the continent also vary with factors such as species, clone, site conditions, region, cultural methods, spacing, harvest strategy, pests and diseases (Hansen et al. 1992; Dickmann 2006). Poplars are particularly sensitive to competition for available light, nutrients and water. Therefore, weed control and nutrition were determined to be essential for maintaining survival, growth and yield of planted poplars (Aird 1962; McKnight and Biesterfeldt 1968; van Oosten 2006; Isebrands 2007). For example, Kennedy (1975) found weed control essential for eastern cottonwood plantings. Czapowskyj and Stafford (1993) found that mowed and fertilized poplar plantations in Maine grew 4 times as fast as the untreated control areas. And Coleman et al. (2006) found that post-establishment fertilized operational poplar plantations grew 3.5 times as fast as unfertilized stands and that fertilizer increased biomass by 40% in the third year.

The early plantations of poplars in North America were planted largely with improved native species (Smith and Blom 1966; McKnight and Biesterfeldt 1968; Heilman et al. 1972). Black cottonwood plantations in the Pacific Northwest grew from 2 to 7 mt/ha per year at close spacing and from 9 to 11 mt/ha per year after coppicing (i.e., resprouting) (Smith and DeBell 1973). Mean annual biomass accumulation of cottonwood plantations in the lower Mississippi Valley averaged approximately 10–13 mt/ha per year at 3 × 3 m spacing with the maximum rate occurring at age 5 without thinning (Krinard and Johnson 1975; Switzer et al. 1976). Francis and Baker (1981) reported annual biomass production of a commercial plantation of a selected cottonwood clone at 3 × 3 m spacing to be 7.6 mt/ha per year in 4 years.

With the advent of the short rotation forestry concept, researchers were anxious to test all of the aforementioned yield factors; many started with small plots. Moreover, forest geneticists quickly designed genetic trials throughout North America to test their new and sometimes old poplar clones (Schreiner 1959; Garrett 1976; Randall 1976; Stettler et al. 1992). In some cases, the native species outgrew the ill-adapted new clones (Blow 1948; Smith 1968; Maisenhleder 1970). There was an early trend toward very close spacing trials with repeated coppicing (Blake 1983; Ferm and Kauppi 1990). Spacing was determined as an important factor for biomass yields, and it had to be coupled properly with rotation age to maximize yield. Early results from Wisconsin in the midwestern United States with a Canadian hybrid poplar by Ek and Dawson (1976) planted at 0.22, 0.3 and 0.6 m² spacing were 11.3, 12.6 and 13.8 mt/ha per year, respectively after 4 years. After 10 years the highest biomass production from a clone and spacing study in Wisconsin was 10.4 mt/ha per year at a 2.4 m² spacing (Zavitkovski 1983). These Wisconsin studies were with poplar clones from the NE poplars and from Canadian cooperators Cram (1960) and Zsuffa (1975). Strong and Hansen (1993), in an overview of 16 years of the Wisconsin studies, stated the maximum mean annual biomass production was 12.8 mt/ha per year by an NE clone planted at 1 × 1 m spacing. They concluded that biomass yield was independent of spacing except that time to maximum biomass (i.e., rotation) and tree size will vary according to spacing.

Block demonstration plantings throughout the midwestern United States of the NE clones planted at 2.4 × 2.4 m spacing yielded from 4.7 to 9.5 mt/ha per year in 8 yrs. The mean annual biomass production peaked at year 10 at 7 mt/ha per year and the “best” sites averaged 9.2 mt/ha per year (Netzer et al. 2002). Berguson (2008) recently presented results of yield tests for commercially managed poplar plantations in the Midwest; yields of current clones produce from 7.8 to 12.3 mt/ha per year.

L. Zsuffa worked in Ontario on poplar breeding and short-rotation forestry throughout his career (Richardson et al. 2007). The “best” poplar clones from his program yielded between 5 and 19 mt/ha per year (Zsuffa 1975; Zsuffa et al. 1977; Anderson 1979). The Ontario Ministry of Forestry growers guide for hybrid poplar presents clonal descriptions and biomass tables for Canadian clones (Boysen and Strobl 1991). At the same time as the Ontario work, G. Vallee and co-workers established a poplar breeding program and conducted biomass trials in Quebec. Results from that breeding program are presented in Dickmann et al. (2001). Labreque and Teodoreseu (2005) reported hybrid poplar yields of 17–18 mt/ha per year at 0.3 × 1.7 m spacing in a coppice study in Quebec.
In the U.S. Northwest, R.F. Stettler of the University of Washington and P.E. Heilman of Washington State University collaborated on a hybridization and cloning program of *P. trichocarpa* that has had a major influence on poplar biomass production in the United States and Canada (Heilman and Stettler 1985; Stettler et al. 1988). The new *P. trichocarpa × P. deltoides* hybrids from that research and development program have been studied widely throughout the region and world and with industrial collaborators has led to extensive poplar commercialization in the Pacific Northwest of North America (Stanton et al. 2002).

Early studies conducted at 1.2 × 1.2 m spacing compared the new hybrids with select native black cottonwood clones. Average biomass production of the black cottonwood varied by clone and was from 5.2 to 23.1 mt/ha per year. However, the new hybrid *P. trichocarpa × P. deltoides* clones were impressive and yielded from 15.6 to 27.8 mt/ha per year. These high yields prompted a series of further research studies on the productivity of the new clones (Heilman and Stettler 1985; Stettler et al. 1988). Heilman and Stettler (1990) studied coppicing of the new hybrids compared to native black cottonwood. Mean yields were 11.3 mt/ha per year for the coppice and 12.6 mt/ha per year for the initial harvest. However, many clones had higher yields after coppice, and there was significant clonal variation in coppice yields that suggested that superior coppicing clones can be selected. D. DeBell and coworkers at the U.S. Forest Service conducted a series of field studies with the Stettler/Heilman clones in the 1990s in western Washington State. They found that poplar clones had uneven yields in monoclonal versus polyclonal blocks at close spacing (i.e., 0.5, 1.0, and 1.5 m spacings). Biomass yields for individual clones ranged from 11.7 to 18 mt/ha per year for these spacings. Monoclonal blocks yielded more biomass than polyclonal blocks. The highest biomass was produced in the closest spacing (i.e., 0.5 m) (DeBell and Harrington 1993; DeBell and Harrington 1997). DeBell et al. (1993) also studied the so-called “wood grass” concept versus more conventional spacings. Two hybrid poplar clones were planted at 0.2 and 0.3m spacing and at wider spacings (i.e., 0.5, 1.0 and 2.0 m). The fast growing Stettler clone, H 11-11, harvested annually produced 7.0 mt/ha per year over 5 years. The yield of the same clone at wider spacing was 18.8 mt/ha per year. During the 5 years, H 11-11 produced over 30 mt/ha per year for a single rotation. They concluded wider spacings and longer cutting cycles outperformed “wood grass.” DeBell et al. (1996) also found biomass differences in the two aforementioned clones planted in monoclonal blocks for 7 years. Clone H 11-11 averaged 18.2 mt/ha per year at 1m spacing for 7 years. DeBell et al. (1997) also studied four clones including black cottonwood and H 11-11 monoclonal blocks at 1 × 1 m spacing. Biomass productivity ranged from 11 to 18 mt/ha per year after 5 years. Hybrid poplar H 11-11 out-produced the native black cottonwood, but production peaked at 4 years at close spacing. Ceulemans et al. (1992) and Scarascia-Mugnozza et al. (1997) also studied the productivity of two Stettler hybrids compared to parental *P. trichocarpa* and *P. deltoides* clones at 1 × 1 m spacing. Clonal ranking for biomass production of 4 years showed the hybrid clones outperformed the parental clones. H 11-11 produced over 35 mt/ha per year whereas the parental clones yielded 16 and 14 mt/ha per year, respectively, for the *P. trichocarpa* and *P. deltoides* clones.

Operational plantings are not as productive as field research studies because of soil heterogeneity, weather, and pests and diseases. DeBell et al. (1997) have reported biomass production rates for operational poplar plantings of 12–17 mt/ha per year in western Washington. Industry researchers Stanton et al. (2002) reported commercial yields of improved poplars averaging 13.8 mt/ha per year with selected hybrid poplars yielding over 20 mt/ha per year in 6 years. These results highlighted the importance of genetic improvement in short rotation poplar culture. When clones from the early stages of hybridization and cloning program produce over 20 mt/ha per year in commercial plantations, even higher yields can be expected when future improved clones become available. These results suggest a “green revolution” of short rotation biomass production is possible with poplar. Just 30 years ago Cannell and Smith (1980) had calculated in their review and appraisal of close spaced hardwoods in temperate regions that the maximum theoretical working production was between just 10–12 mt/ha per year.
15.4.2.2 Europe

Europe obviously has a long rich history of poplar plantations. Notably much of the European interest in poplar came when European explorers returned from North America with handsome poplar specimens that they subsequently planted in their gardens. Spontaneous hybrids that resulted gave rise to poplars known as “intercontinental” or “Canadian” poplars. Another popular European introduction was the “Carolina” poplar—a cottonwood from southeast United States (FAO 1980; Dickmann 2006). The new poplar hybrids were first planted along waterways and roadways. Remarkably Claude Monet, the French impressionist painter, loved poplars and became a poplar plantation owner in 1891 when his favorite poplar models depicted in his famous “Poplars” series were about to be cut by the village (Tucker 1989). The “Euramerican” poplars, a natural hybrid of *P. deltoides*, and *P. nigra* (now known as *P. canadensis*), were planted widely throughout Europe between 1900 and World War II (FAO 1980).

An important milestone in the advancement of European poplar culture was the establishment of the Instituto Sperimentazione Pioppicoltura at Casale Monferrato, Italy, during World War II (Dickmann 2006). This institute, still active today, was involved in creating many new poplar clones (such as I-214) and development of poplar culture. The clones produced in Casale were planted throughout Europe and are still widely planted throughout the world. Another important European milestone was the founding of the International Poplar Commission (IPC) in 1947 in Rome under the auspices of the United Nations Food and Agriculture Organization (FAO) (Pourtet 1976; Viart 1976). This organization also exists today with a mission to promote all aspects of poplar culture for improving rural livelihoods worldwide. In recent years, the IPC is becoming more active in promoting the uses of poplars for bioenergy.

After WW II, there was a revival of breeding and growing poplars in Europe albeit for conventional wood products. Poplar breeding began in the United Kingdom in the early 20th century (Henry 1914), but breeding programs took some time to evolve (Schreiner 1959). Pauley (1949) and Muhle-Larsen (1970) reviewed advances in poplar breeding in Europe. There were many active poplar breeding programs/breeders in Italy (Piccarolo), Netherlands (Koster), Belgium (Steenackers), Germany (Weisberger), and Spain (FAO 1980). Most of these breeders actively cooperated with North American breeders in the exchange of information and materials.

Thousands of hectares were planted to poplars in the ensuing years in Europe. According to the IPC (FAO 2008), there are currently 236,000 ha of poplar plantations in France, 118,500 ha in Italy, 100,000 ha in Germany, 98,500 ha in Spain, and thousands of hectares in other countries such as Croatia and Romania. Many of these plantations were planted in the 1950s and 1960s.


In Europe, poplars have been largely grown at wide spacings for timber and traditional wood products in modern times. Notably, FAO (1980) made little mention of the use of poplars for energy except in some eastern countries where poplars were grown for fuelwood. In the 1960s, this tradition began to change toward growing poplars at close spacings and on shorter rotations. The goal was to produce more wood per unit of land area in a shorter time frame for wood fiber and energy (Mitchell et al. 1992). Eastern European countries embraced short rotations very early. Markovic et al. (2000) reported short rotation poplar test plantations as early as 1960 with many poplar clones and varieties and many spacings and cutting cycles. Marosvolgyi et al. (1999) reported long term studies of poplars for bioenergy in Hungary. European biomass studies differed from North American in that more poplar species and species hybrids were tested, and coppicing was early on accepted as a means of increasing poplar biomass production per hectare. Avanzo (1974) reported tests of 600 *P. deltoides* clones, 148 clones of *P. nigra*, and 73 *D × N* hybrids for biomass production.
on 3–5 year rotations. Most of the European studies of short rotation poplars were still at traditional wide spacings (Louden 1976).

Ceulemans and Deraedt (1999) reviewed the potential of poplars grown under short rotation culture for bioenergy. They outline that the way to optimize biomass productivity is to optimize plant genotype or cultural management regime, or the interaction between both. Their review compares many poplar clones, spacings and climates under coppicing (Ferm and Kauppi 1990) and noncoppicing regimes. They found that there are clonal differences in biomass yields under different coppicing regimes and reported yields of 20–30 mt/ha per year. In some cases the noncoppiced clones yielded more than the coppiced (Proe et al. 2002). Cannell and Smith (1980) concluded that the “working maximum” for short rotation forests was theoretically 10–12 mt/ha per year with a possible increase of 10–20% with coppicing. At the time, this upper limit seemed reasonable with existing clones. We know now that yields can be increased further with genetically improved material and coppicing. For example, Pontailler et al. (1999) reported biomass yields of 4 poplar clones at 0.8 m spacings over 5 coppices and found the highest biomass yield was over 30 mt/ha per year! Improved genetic material does make a difference (Ceulemans 2004). Benetka et al. (2007) found that native P. nigra clones produced much less than an NE U.S. hybrid. However, in some regions the use of native plant material is required. They cited disease resistance as an important factor in biomass yield.

R. Ceulemans and co-workers conducted a series of studies in the late 1990s to identify coppicing differences in biomass production in short rotation poplar (Ceulemans 2004). Laureysens et al. (2003, 2004) reported results of the first rotation coppice study in Belgium. After 6 years the biomass production of 17 poplar clones varied with clone; mortality of stools was also clone related. Biomass production was 1.6–10.8 mt/ha per year (Table 15.5). The “best” clone was a T × D hybrid. Laureysens et al. (2005) reported results of the second rotation of short rotation coppice culture of poplar of the above study. Notably the results of the second rotation were significantly different than the first. The P. nigra had biomass yields at 9.7 mt/ha per year, but the first rotation “best” T × D clones performed poorly. Melampsora rust played an important part in determining

### Table 15.5
**Chronological Synthesis of Poplar Biomass Production Field Studies and Plantations by Location in Europe**

<table>
<thead>
<tr>
<th>Location</th>
<th>Clone/Species</th>
<th>Age (years)</th>
<th>Spacing (m)</th>
<th>Productivity (mt/ha per year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>T</td>
<td>5</td>
<td>0.5</td>
<td>9–10</td>
<td>Cannell and Smith (1980)</td>
</tr>
<tr>
<td>Finland</td>
<td>B</td>
<td>6</td>
<td>0.7–1.4</td>
<td>4.2</td>
<td>Ferm et al. (1989)</td>
</tr>
<tr>
<td>France</td>
<td>TD</td>
<td>2–3</td>
<td>Multiple</td>
<td>0.6–3.5</td>
<td>Auclair and Bouvarel (1992)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>TD, T</td>
<td>4</td>
<td>1.0–2.0</td>
<td>13.6</td>
<td>Armstrong et al. (1999)</td>
</tr>
<tr>
<td>Belgium</td>
<td>TD</td>
<td>Multiple</td>
<td>0.8</td>
<td>30</td>
<td>Pontailler et al. (1999)</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>B</td>
<td>5</td>
<td>1.5</td>
<td>10.2–16.2</td>
<td>Proe et al. (2002)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Multiple</td>
<td>6</td>
<td>0.75–1.5</td>
<td>10.8</td>
<td>Laureysens et al. (2003)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Multiple</td>
<td>4</td>
<td>1.0</td>
<td>2.8–11.4</td>
<td>Laureysens et al. (2004)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Multiple</td>
<td>Multiple</td>
<td>1.0</td>
<td>9.7</td>
<td>Laureysens et al. (2005)</td>
</tr>
<tr>
<td>Sweden</td>
<td>T,TD</td>
<td>13</td>
<td>1.2</td>
<td>8.0</td>
<td>Christersson (2006)</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>N,MT</td>
<td>4–7</td>
<td>2.1</td>
<td>7.6–9.4</td>
<td>Benetka et al. (2007)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Multiple</td>
<td>3</td>
<td>0.75–1.5</td>
<td>2.8–9.7</td>
<td>Al Afas et al. (2007)</td>
</tr>
<tr>
<td>Belgium</td>
<td>Multiple</td>
<td>11</td>
<td>0.75–1.5</td>
<td>13.3–14.6</td>
<td>Al Afas et al. (2008)</td>
</tr>
</tbody>
</table>

* B, P. balsamifera; D, P. deltoides; N, P. nigra, T, P. trichocarpa, DN, D × N; TD, T × D; M, P. maximowiczii; MT, M × T.
biomass production in the second rotation. Al Afas et al. (2008) summarized the biomass yields over 3 rotations (11 years) from the above studies at Boom, Belgium. Biomass production varied with clone and rotation. Biomass increased from year to year within a rotation, but declined with number of rotations. The N × T hybrids were the “best” overall performing clones and were “best” adapted to multiple coppice rotations.

Recent EU policy changes have had a major effect on efforts to find high yielding poplar biomass systems. The goal is to double EU renewable energy use from 6 to 12% by 2010 (Klasnja et al. 2006). Therefore, there has been an increase in the poplar biomass production studies in Europe. Sixto et al. (2006) reported 18 new experimental studies of poplars with very high density plantings (i.e., 15,000–33,000 trees/ha) of many poplar clones. Their goal is to identify high biomass producers while providing environmental benefits and rural employment. Scarascia-Mugnozza et al. (2006) reported 5000 new ha of poplar plantations in northern Italy. New clones improve yields by 100%, yielding 18–24 mt/ha per year. The studies also investigated the use of animal and urban wastewater for irrigating short rotation poplar plantations. More recent results are even more favorable. New clones with N fertilization are producing an average of 23 mt/ha per year and have achieved up to 50 mt/ha per year (Paris et al. 2008). The Italian Ministry of Agriculture has also recently financed new research on poplar biomass supply chains.

The goal is to use poplar biomass for feeding district heating plants. Early results confirm biomass yields of 20–25 mt/ha per year planted at different spacings and rotations (Facciotto et al. 2008; Nervo et al. 2008).

15.4.2.3 Other Countries

The largest poplar plantations in the world are in China. China has over 4.3 million ha of poplar plantations and an additional 2.5 million ha of poplars used in agroforestry (FAO 2008). India also has vast areas of poplars used for agroforestry (Puri and Nair 2004), and Turkey has over 138,000 ha of planted poplars; again, large areas are planted under agroforestry with poplars interplanted with beans, corn and melons (Toplu 2008). There are large areas of poplars used for agroforestry and silvo-pasture in New Zealand (FAO 2008), and in the 1960s there were plantations of poplar in Australia and South Africa (Pryor and Willing 1965). There are also an increasing number of poplar plantations in South America (Eaton 2008b).

Small farmers in China, India and Turkey have been using poplars for fuelwood since antiquity, but until recently poplar plantations were used mostly for traditional wood products and not bioenergy. Fang et al. (1999) reported 6 year results of short rotation poplars in China with annual biomass increments of 17 mt/ha per year. Biomass yields differed considerably with planting density, clone and rotation length. In later reports, Fang et al. (2006, 2007) reported biomass yields of 14.6 mt/ha per year for three poplar clones at age 10. Das and Chatuverdi (2009) reviewed biomass production of poplars in agroforestry systems in India and reported biomass yields of 5–10 mt/ha per year. Dhanda and Kaur (2000) also reported on poplar biomass production in an agri-silviculture system in Punjab, India. There is great potential in South America for growing poplars for biomass production. Eaton (2008b) reported test yields of genetically improved poplars of 30 mt/ha per year in Chile.

15.4.3 Bioenergy from Poplars

Interest in biomass for energy accelerated after WW II (Young 1973). Wood energy plantations were seen as a way of achieving energy independence. Szego and Kemp (1973) were early proponents of the “energy forests” or fuel plantations. Up until that time, short rotation plantations were viewed as a solution for maximizing fiber yield and taking the pressure off of native forests to help provide the nation’s pulpwood supply (Dawson 1976). Then, came the OPEC oil embargo in 1973. The embargo changed the public and government attitude toward alternative energy sources, such as biomass. Notably, Stephens (1976) gave the keynote address at an International Cottonwood Symposium.
promoting poplar biomass as an energy source. Tillman (1976) reviewed the potential of wood as an alternative fuel at that time. Clearly, high biomass yields of plantations were needed to make fuel plantations feasible.

Zavitkovski et al. (1976) outlined the potential of using poplar hybrids as a source of wood and energy. Soon after, Isebrands et al. (1979) examined the potential of an integrated utilization strategy for biomass from short rotation poplars. The strategy provided alternatives, including 1) pulp only, 2) energy only, 3) pulp and fuel and 4) pulp, fuel and animal feed. The case study used was a 5-year-old hybrid poplar plantation grown at 1.2m spacing. The biomass yield was 8.4 mt/ha per year for pulp or 200 MKcal/ha for energy. Energy values determined for NE poplar clones in Wisconsin (Strong 1980) were used to calculate the high heating value of the biomass. The caloric values of poplar clones were relatively similar, ranging from 4636 to 4755 cal/g or 1.9–2.0 \times 10^4 \text{J/g} (i.e., 19 MJ/kg). These results are similar to those of Bowersox et al. (1979) with other clones. Their values also agreed closely with those provided by Sastry and Anderson (1980) for juvenile poplar clones grown in Canada and more recent findings (Klasnja et al. 2006). There are 4.2 joules in a calorie in biomass. So, the poplar biomass plantation produced over 200 Mkcal/ha (8.4 \times 10^4 \text{J/ha}). A high heating value of 200 Mkcal/ha in 5 years is equivalent to 40 Mkcal/ha per year or 27 barrels of oil equivalent per ha. Their analysis assumed each barrel of oil equals 1.48 Mkcal or 6.1 \times 10^9 \text{J}.

With each ton of poplar biomass equating to more than 3 barrels of oil equivalent, 30 mt/ha equals 90 barrels of oil!

For the energy plantation concept to work successfully, the energy output/input ratio must be positive. Therefore, biomass energy produced must exceed the energy spent on production and harvesting (Anderson et al. 1983). Zavitkovski and Isebrands (1985) analyzed the energy output/input ratio in short rotation hybrid poplar and found them favorable. Anderson et al. (1983) in a thorough review of energy plantations concluded that one must maximize bioecological factors, genetic materials, and cultural factors to maximize biomass yields of an energy plantation. Therefore, there is a premium placed upon achieving as much biomass per ha as possible to be successful. Kauter et al. (2003) conducted an analysis of quantity and quality of Populus short rotation coppice systems for energy in European systems. Notably, their energy content was very similar to those found in the North American studies. And, the energy content of the short rotation poplar biomass was similar to caloric values of native aspen stands in Canada (Peterson et al. 1970). Christersson (2008) made an energy comparison of short rotation poplar with agricultural crops in Sweden. According to his analysis, the poplar biomass crops compare more favorably in energy balance than sugar beet and wheat in Sweden.

### 15.4.4 Limitations and Challenges

Despite the promise of using poplar biomass for bioenergy, there are many limitations and challenges that must be overcome. These limitations can be classified into several categories including biological, technical, economic, political and psychological (Anderson et al. 1983; Hoffman and Wieh 2005; van Rees 2008). These categories are closely interrelated and often have multiple interactions. Despite the huge genetic gains that have been made in biomass yields through genetic hybridization and cloning programs, the major factor affecting the production costs of bioenergy is biomass yield. Thus, the emphasis placed on biomass production in this chapter. The consensus is that biomass yields will have to be at least 15–20 mt/ha per year to compete with fossil fuels (Anderson et al. 1983), and some analysts believe 20 mt/ha per year may not be enough given recent economic conditions (Gallagher et al. 2006). They concluded that yields will need to be increased by 40% through improvements in genetics and silvicultural practices to make short rotation biomass plantations cost effective. Genetic improvements take considerable time, but “best management practices” for growing poplars have recently been developed (van Oosten 2006; Isebrands 2007). However, climate effects and diseases are also very important (Anderson et al. 1983; Kauter et al. 2003). Other important variables in economic analysis of
Forest Trees

Growing poplars have been known for many years. They include: land prices, planting stock, fuel, labor, site preparation, maintenance, fertilizer, irrigation, harvesting, drying, handling, transportation, taxes, and insurance as well as market values at harvest (Lothner 1983; Yemshanov and McKenney 2008). These variables have not changed over the years, but the absolute costs and revenues have changed markedly (Isebrands 2007). Economic variables also vary with the technology used to produce fuels and chemicals from biomass. There are many conversion technologies possible for use with woody biomass—new and old. They include pyrolysis, gasification, liquefaction, ethanol production by hydrolysis, and other biochemical processes (Phelps 1983). Unfortunately, although all are technically feasible, none are presently economical on a commercial basis without subsidy (Christersson 2008). Recent developments suggest cellulosic ethanol will become economic (Decker 2009).

A major limitation can be the availability of markets and proximity to markets (Hoffman and Wieh 2005). For example, without a viable market, nurserymen are reluctant to risk investment in scaling up genetically improved clones, and without large numbers of improved plant materials, large biomass plantations are not possible (i.e., “the chicken and egg” effect). With such uncertainty, financial credit is often difficult to secure. These factors affect the mindset or psychology of farmers who might change from traditional crops to biomass crops (van Rees 2008).

When it comes to cellulosic ethanol from biomass, there are a number of hurdles to commercializing the process (Alexander and Gordon 2009). One is difficulty in raising capital for a project without a cash flow. Another hurdle is the need to convince farmers that a market for their product will emerge. Moreover, there is uncertainty about the production and transportation costs of a new crop and product. In addition, the land availability for cellulosic ethanol biomass may be distant from the access to populated areas where the ethanol is needed, thereby increasing costs. Finally, there is a political hurdle that is termed the: “blend wall”, i.e., the percent of ethanol blend allowed in gasoline. Unless the blend percentages are increased, this factor could be a major hurdle. All of these factors are inherent in the development of a new crop with new conversion technology (Sims et al. 2009). Dallenmand et al. (2008) summarized the challenges faced with implementing biomass energy in the EU. These challenges include (1) supply industry with raw material year-round, (2) ensure a harvest window, (3) ensure harvest and collection efficiency, (4) improve energy processing technologies, (5) develop reliable storage and transport systems, (6) optimize feedstock quality, (7) optimize biomass pellet technology, and (8) develop efficient logistical structure such as fuel depots. All of the limitations and challenges are a part of the development of any new crop and conversion technology.

15.4.5 Future Considerations and Conclusions

Despite the numerous limitations and challenges to commercializing poplar bioenergy, there are a number of promising developments and opportunities for poplar biomass ahead. For example, there are some important policy developments that will affect biomass for energy. At the 17th European Biomass Conference in Germany in July, 2009, high officials from the German Ministry of the Environment and the U.S. Department of Energy spoke about their country’s commitment to biomass as an alternative energy source. Moreover, the United States is now participating in International Climate Change talks. This development should help short rotation woody crops reach their potential for part of a carbon management framework (Tuskan and Walsh 2001). Zabek and Prescott (2005) have shown that the carbon content of poplar biomass plantations ranges from 74 to 89 Mg/ha in 14 years. Moreover, in China, which has the largest number of poplar plantations in the world, Fang et al. (2006) has shown that the carbon sequestration potential in China alone is $3.8 \times 10^7$ mt/ha per year.

As the CO$_2$ concentration in the world increases, there are some potential opportunities for poplar culture. Liberloo et al. (2006) working at the EUROFACE site has shown that poplars are growing much faster in a CO$_2$ rich environment. So, it is hoped that landowners worldwide someday will
be able to receive carbon incentives to help make poplar biomass plantations more economically feasible (Yemshanov and McKenney 2008).

Another encouraging development is the recent sequencing of the poplar genome by molecular biologists (Tuskan et al. 2006). This new development should allow geneticists to improve growth, disease resistance and chemical composition of poplars in the future (Taylor 2002, 2008; Wullschleger et al. 2005). There now may be opportunities for genetic engineering of herbicide resistance into poplars (i.e., Roundup Ready poplars) and improved cellulosic biosynthesis needed to make cellulosic ethanol more economical (Joshi et al. 2004; Sims et al. 2009).

There are some possible policy decisions that could make cellulosic ethanol more competitive, but they are not yet available (Carling 2009). But there are still other limitations that include production and transportation costs as well as access to land in populated areas (Alexander and Gordon 2009). Notably, Greenwood Resources, Inc., and ZeeChem are currently building the first poplar demonstration biorefinery to produce cellulosic ethanol in Boardman, OR. It is scheduled to open in 2010 (Eaton 2008a).

Europe is ahead of the rest of the world in development of poplar biomass crops for power production, probably because of incentives. In Italy, four power plants of the energy company Power Crop that will use poplar biomass as a feedstock are under construction. These facilities will require 30,000 ha of land dedicated to short rotation poplar coppice plantations to feed them. The commercial plantations were scheduled to become operational in 2009. Another power company near Milano, Italy, is constructing a small power plant that will utilize poplar biomass from 3000 ha of poplar plantations nearby. Another European power company, RWE, is planting 10,000 ha of short rotation poplar coppice to feed a co-fired coal power plant in Germany. RWE has plans to develop other facilities in Romania and Spain that will utilize poplar biomass. A French power company also has plans to use 1000 ha of short rotation poplar coppice for a co-fired power plant in Hungary. And, in the United Kingdom, the Drax power company is planning on building three power plants that will utilize local poplar biomass. They presently have a power plant that utilizes imported wood pellets for fuel. These power plants are able to economically use poplar biomass because of the EU tax policies aimed at reducing CO2 emissions to the atmosphere. There have already been several successful biomass fired power plants in Northern Ireland and Sweden using willow biomass. The short rotation willow coppice system was developed by a research group at the Swedish University of Agricultural Science in Uppsala, Sweden (Perfut 1989).

Poplar biomass will likely be used for fuel in developing countries for years to come. However, there is a worldwide increase in the use of poplar wood residues for energy production in small forest products industries and businesses in developing countries, especially China and India. Moreover, there is a trend toward co-firing poplar biomass with coal for electricity generation in some countries to decrease costs and improve air quality (De and Assadi 2009). This trend will likely continue to increase in the future because of the shrinking world economy.

The cellulose ethanol industry in Europe is still undergoing development as in North America (Slade et al. 2009). Poplars are one of the several preferred biomass feedstocks under study, and North America companies may build or acquire poplar based cellulosic ethanol plants in Europe once this technology has been commercialized. Thus, the successes in the next few years will likely determine the future success of commercialization of poplar bioenergy throughout the industrialized world.

There are also encouraging developments for the use of poplars for their environmental benefits. Short rotation woody crops can provide ways of cleaning up (i.e., phytoremediation) polluted water and soils (Perfut 1989; Licht and Isebrands 2004). There are many intangible benefits that short rotation poplars for biomass production provide including soil erosion control, protection, wildlife benefits, air quality improvement, carbon sequestration, aesthetics and psychological benefits (Licht and Isebrands 2004; Isebrands 2007). All of the aforementioned developments point toward a promising future for the use of poplars as a bioenergy source.
15.5 OTHER FOREST SPECIES BIOENERGY USE AND POTENTIAL WORLDWIDE

In addition to Eucalyptus, Pinus, and Populus species, many other trees have promise for bioenergy production in various parts of the world. Salix species covered in Section 3, Chapter 4 of this book are well suited to wet temperate climates. Numerous others have been proposed for use in different climatic zones (Little 1981; NAS 1977, 1979, 1980, 1982; NRC 1983a, 1983b, 1983c, 1984).

Humid Tropics—Acacia auriculiformis, A. mangium, Albizia falcataria, Bursera simaruba, Calliandra calothyrsus, Casuarina equisetifolia, Coccoloba uvifera, Derris indica, Gliricidia sepium, Gmelina arborea, Guazuma ulmifolia, Hibiscus tiliaceus, Leucaena leucocephala, Maesopsis eminii, mangrove genera, Mimosa scabrella, Muntingia calabura, Psidium guajava, Sesbania bispinosa, S. grandiflora, Syzygium cumini, Terminalia catappa, Trema spp.

Tropical Highlands—Acacia decurrens, A. mearnsii, Ailanthus altissima, Alnus acuminata, A. nepalensis, A. rubra, Gleditsia triacanthos, Grevillea robusta, Inga vera, Melaleuca quinquenervia, Melia azedarach, Robinia pseudoacacia, Sapium sebiferum


Many of these are multipurpose trees that have more than bioenergy uses. They tend to have many favorable characteristics such as wide adaptability, easy establishment, low maintenance requirements, tolerance of difficult environments, nitrogen-fixing ability, rapid growth, coppicing, and high energy content. Those that are multistemmed, poorly formed, and short-lived may be best for family and small-scale use. Most are suitable for plantations to meet larger-scale bioenergy needs. Because these species are aggressive, grow rapidly, and often seed early and prolifically, they are potentially invasive and should be used carefully. Native species should always be strongly considered for bioenergy plantations.

15.6 PRETREATMENT OF FOREST BIOMASS

Biochemical conversion of lignocellulosic biomass through enzymatic saccharification and fermentation is a major pathway for liquid fuel production from biomass (USDE 2005; NSF 2007). In this approach, biomass cellulose is converted to glucose through microbial or enzymatic actions. The glucose is then fermented into alcohols, such as ethanol. Residues resulting from microbial and enzymatic actions contain mainly lignin and can be converted to energy thermochemically. Whereas starch functions as an energy storage material in plants, wood functions as a structural material. As a result, woody biomass has natural resistance—often called “recalcitrance”—to microbial and enzymatic deconstruction (Himmel et al. 2007). Forest (woody) biomass differs from agriculture biomass physically, structurally, and chemically. Specifically, forest biomass is physically large and structurally very strong. Its density is higher than agricultural biomass. It has higher lignin, higher cellulose, and lower hemicellulose contents than most agricultural biomass. As a result, forest biomass has much greater recalcitrance than does agricultural biomass. On the other hand, the high density and high lignin and cellulose content increase energy content and reduce transportation cost for forest biomass, which is favorable for advanced energy production.

Recalcitrance of lignocellulosic biomass is a major barrier to economical development of bio-based fuels and products through the biochemical pathway. This is especially true for forest biomass because it has greater recalcitrance than does agriculture biomass. The technical approach to overcome this recalcitrance has been pretreatment to make cellulose more accessible to hydrolytic enzymes for
conversion to glucose. Both physical and chemical pretreatments have been used to achieve satisfactory conversion of lignocellulose. Physical pretreatment refers to the reduction of physical size of forest biomass feedstock to increase enzyme-accessible surface areas (Lynd 1996; Zhu et al. 2009) and decrease the crystallinity of cellulose. Chemical pretreatment refers to the process of using chemicals to remove or modify key chemical components that protect cellulose in biomass, mainly hemicellulose and lignin. Chemical pretreatment often provides a good separation of hemicellulose in the form of sugars from cellulose for high-value utilization, including liquid fuel through fermentation.

15.6.1 Physical Pretreatment of Forest Biomass—Physical Size Reduction

The issue of physical size reduction has been largely overlooked in the lignocellulosic ethanol research community. The reason is likely in part that most lignocellulosic ethanol research has focused on using agricultural biomass that does not need a significant amount of mechanical energy to achieve satisfactory size reduction. However, size reduction is very energy intensive for forest biomass. In wood-fiber production, size reduction is in two steps. The first step is coarse size reduction, reducing wood logs to chips of 10–50 mm in two dimensions and 2–10 mm in the third dimension. The second step is to further reduce the wood chips to fibers of millimeters in length. Energy consumption in the first step is much lower than that in the second step.

A simple energy balance calculation using forest biomass demonstrates the importance of size reduction for biomass refining. Assume that ethanol yield from wood is about 300 L/tonne of oven-dried wood with current technology. Higher heating value of ethanol is about 24 MJ/L, which gives total wood ethanol energy of 7.2 MJ/kg wood. Typical energy consumption to produce wood chips is about 50 Wh/kg; energy consumption in the second step through disk milling can be anywhere from 150 to 700 Wh/kg (Schell and Harwood 1994), depending on the fiberization process and the degree of milling. With these assumptions, total size-reduction cost is 200–600 Wh/kg, which is equivalent to 0.72–2.16 MJ/kg, or 10% to 30% of the wood ethanol energy available.

Three factors affect energy consumption during size reduction: the degree of size reduction, the fiberization mechanism, and chemical or biological pretreatment before size reduction. All of these factors also affect enzymatic cellulose saccharification. Most of the existing literature on size reduction relates to pellet, fiber, and wood flour production. Few studies on biomass size reduction have taken an integrated approach to examining energy consumption, enzyme-accessible substrate surface, and chemical pretreatment efficiency in terms of enzymatic cellulose conversion. Most reported work on size reduction has not involved cellulose conversion (Schell and Harwood 1994; Cadoche and Lopez 1989; Mani et al. 2004) and has addressed only energy consumption and substrate size. On the other hand, reports on enzymatic hydrolysis using size-reduced substrates did not provide information about energy consumed to produce the substrate and/or a careful and complete characterization of substrate size (Allen et al. 2001; Zhu et al. 2005; Nguyen et al. 2000). At most, substrates were characterized by sieving or screen methods (Sangseethong et al. 1998; Chundawat et al. 2007; Dasari and Berson 2007; Hoque et al. 2007). Consequently, there is a knowledge gap linking energy consumption, substrate surface, and pretreatment efficiency.

15.6.1.1 Degree of Size Reduction and Substrate-Specific Surface

To address the degree of size reduction, proper characterization of forest biomass substrate is necessary. The geometric mean diameter of the substrate particles measured by traditional sieving and screen methods has been almost exclusively used for biomass substrate size characterization (Mani et al. 2004). This size measure is significantly affected by biomass substrate morphology, such as particle aspect ratio (Zhu et al. 2009). Most size-reduction processes produce fibrous substrate with a wide range of particle (fiber) aspect ratio of 5:100. As a result, existing data on substrate size characterization have limited value. Enzyme-accessible surface area is of most interest for saccharification. Holtzapple et al. (1989) calculated specific surface area based on a spherical particle assumption to correlate energy consumption for comparing the efficiencies of several size-reduction processes. The spherical
model for specific surface calculation is justifiable for particles with close to unity-aspect ratio, such as wood sawdust, but is questionable for most forest biomass substrates consisting of fibers. Recently, we developed a wet-imaging technique for the characterization of forest biomass substrate (Zhu et al. 2009). In this technique, the two dimensions of each substrate fiber are measured in a flowing water channel by an optical microscopy using a charge-coupled device (CCD) camera (Figure 15.2).

The total surface and volume of the substrate can be calculated using a cylinder model for each fiber. The volumetric specific surface can be determined by dividing the total surface of a sample by its volume [eq. (15.1)] (Zhu et al. 2009). For most mechanically derived substrates, the cylinder assumption is reasonable, as confirmed by scanning electron microscope pictures of the substrates (Zhu et al. 2009). If the substrate particles are spherical like sawdust, then a spherical model can be used to determine specific surface [eq. (15.2)].

\[
S_f^V = \frac{A_f}{V_f} = \frac{\sum n_i (d_i^2 + 2 \cdot d_i \cdot L_i)}{\sum n_i d_i^2 \cdot L_i} = \frac{4 \sum n_i d_i (L_i + d_i/2)}{\sum n_i L_i \cdot d_i^2} = 4 \cdot \frac{\sum n_i L_i \cdot d_i}{\sum n_i d_i^2} = \frac{4}{D_{21}} \tag{15.1}
\]

\[
S_p^V = \frac{A_p}{V_p} = \frac{\sum n_i d_i^2}{\sum n_i d_i^3} = \frac{6}{D_{32}} \tag{15.2}
\]

$S$ and $A$ are the specific surface and total surface area of the substrate, respectively. Subscript $f$ and $p$ are fiber (cylinder model) and particle (sphere model), respectively. $D_{21}$ is fiber-length weighted-surface-length mean fiber diameter or “width.” $D_{32}$ is often called Sauter mean diameter (SMD). With this wet-imaging technique, we were able to objectively compare the efficiencies of different size-reduction and chemical pretreatment processes in terms of size-reduction energy consumption and cellulose to glucose conversion.

The specific surface can be used to measure the degree of size-reduction. Zhu et al. (2009) used specific surface to successfully measure the efficiency of various size-reduction processes.

15.6.1.2 Fiberization Mechanism

Energy consumption in mechanical pulping of wood depends significantly on how wood chips are fiberized. Refiner mechanical pulps (RMP) are produced under atmospheric refining conditions,
with wood chips fractured through the lumen of wood tracheid. Thermomechanical pulps (TMP) are produced using low-pressure steam (~2.4 × 10^5 Pa, ~134°C) to soften wood chips before disk refining. The wood chips are fractured in the S1 and S2 layer of cell wall.

Medium-density fiberboard pulps (MDF) are produced under increased steam pressure of >5 × 10^5 Pa. In the MDF production process, wood chips are fractured in the lignin-rich middle lamella (ML). This is because the steam temperature reaches the glass transition temperature of lignin (Irvine 1985). Figure 15.3 is a schematic of various fracture mechanisms of wood chips during fiberization. Energy consumption of different pulping processes varies significantly. Typical energy consumptions for producing RMP, TMP, and MDF are about 600, 450, 150 Wh/kg oven-dried wood, respectively. Energy consumption for chemical-thermomechanical pulp (CTMP) is just lower than that for TMP. The surface chemical compositions of these pulps are very different. RMP exposes mostly cellulose on fiber surfaces. MDF fibers are lignin-coated on their surfaces. This can be clearly seen from the color of these pulps, with RMP being the lightest and MDF being brown. The difference in surface chemical composition certainly affects cellulose enzymatic conversion to glucose, as revealed in our previous study (Zhu et al. 2009). The significant variations in mechanical energy consumption of these different pulping processes may provide avenues for potential energy savings in biomass size reduction. However, attempts have not yet been taken to explore this potential.

15.6.1.3 Effect of Chemical Pretreatment
The third factor affecting size-reduction energy consumption and enzymatic cellulose saccharification is chemical pretreatment. Most of the enzymatic cellulose saccharification research has used size-reduced substrate for the purpose of reducing substrate recalcitrance to achieve high cellulose conversion (Nguyen et al. 2000; Allen et al. 2001; Zhu et al. 2005). In fact, to achieve good chemical penetration and therefore effective pretreatment, size reduction before chemical pretreatment is necessary for the dilute acid process (Lynd 1996), one of the most investigated chemical pretreatment processes for lignocellulosic ethanol production. Chemical pretreatment alters the chemical composition and physical structure of biomass by partly removing some cell-wall components, such as hemicellulose and lignin. As a result, size reduction after chemical pretreatment can reduce energy consumption. This energy savings may be insignificant for some agricultural biomass, such as corn stover or switchgrass, but can be very significant for forest biomass (Zhu et al. 2010). This suggests

that post-chemical pretreatment size reduction is not only preferred (Figure 15.4) to take advantage of chemical pretreatments for economical size reduction, but also necessary for the economical biochemical conversion of forest biomass as discussed previously. Furthermore, different chemical pretreatments alter biomass structure to various degrees and therefore affect post-pretreatment size-reduction energy savings (Zhu et al. 2010). For example, the SPORL pretreatment (Zhu et al. 2009) of wood chips is much more effective to reduce size-reduction energy consumption than the dilute acid pretreatment conducted at the same pretreatment time, temperature, and acid charge conditions (Zhu et al. 2010).

This post-chemical pretreatment size-reduction process flow design has several benefits: (1) it takes advantage of chemical pretreatment to alter wood structure to reduce energy consumption in the subsequent size-reduction process; (2) it avoids the difficulties and high-energy consumption for mixing high-consistency pulp with chemicals in pretreatment when size-reduced substrate is used; (3) it can reduce thermal energy consumption in chemical pretreatment; and (4) it can potentially produce a concentrated hemicellulose sugar stream to reduce concentration cost. The rationale for benefits 3 and 4 is that a lower liquid-to-wood ratio can be used in the chemical pretreatment of wood chips than that in pretreatment of fiberized wood pulps. Liquid uptake of fiberized wood pulps is much higher than that of wood chips because of the porous and hydrophilic nature of wood.

15.6.2 Chemical Pretreatment of Forest Biomass

Existing enzymes cannot effectively convert lignocellulose to fermentable sugars without chemical pretreatment. Few pretreatment technologies are capable of effectively removing recalcitrance of forest biomass, especially softwood, to achieve satisfactory cellulose conversion to glucose. Because of the large amount of energy required in size reduction for forest biomass, a viable pretreatment process for forest biomass needs to be not only effective in removing recalcitrance but also capable of doing so before wood size reduction (i.e., on wood chips, not on fiberized materials). This makes pretreatment of forest biomass much more difficult than and different from agriculture biomass, which has not been well recognized by the research community. The most studied and currently widely adopted process in commercial demonstration (i.e., dilute acid process) developed a century ago has been shown to be ineffective for almost all wood species. Acid-catalyzed steam explosion, organosolv, and sulfite pretreatment to overcome recalcitrance of lignocellulose (SPORL) (Zhu et al. 2009) are the only three processes that have demonstrated effectiveness for forest biomass bioconversion.
15.6.2.1 Acid-Catalyzed Steam Explosion

Steam pretreatment was derived from a failed steam explosion pulping process (Kokta and Ahmed 1998). In acid-catalyzed steam explosion, SO$_2$ (De Bari et al. 2007) or sulfuric acid (Ballesteros et al. 2006; Sassner et al. 2008) has been used as a catalyst. Wood chips are often first impregnated with acid catalyst, either in gas phase with SO$_2$ or in the aqueous phase with sulfuric acid, before steam pretreatment. The further size reduction to fiber or fiber bundle level is accomplished through steam explosion. Acid-catalyzed steam pretreatment is actually another form of dilute acid pretreatment in which the pretreatment is carried out in the vapor phase rather than in the aqueous phase. The explosion feature has now been used by many dilute acid operations for further size reduction. Therefore, the difference between dilute acid and acid-catalyzed steam pretreatment is becoming less clear. Catalyzed steam pretreatment works well with hardwood when pretreatment is conducted at an elevated temperature of around 210°C (De Bari et al. 2007; Sassner et al. 2008). The effectiveness on hardwood is achieved at the expense of the large amount of energy consumption in steam explosion. Typical energy consumption for the pretreatment at 210°C is about 1.8 MJ/kg oven-dried wood, even after accounting for low-quality steam recovery. The conversion of softwood cellulose is less satisfactory than that of hardwood (Duff and Murray 1996). Furthermore, total hemicellulose and glucose yield from pretreatment and enzymatic hydrolysis is about 70% (Gable and Zacchi 2002). Typical pretreatment conditions for wood are temperatures around 210°C and SO$_2$ or sulfuric acid charge of 1–2% on oven-dried wood. Pretreatment time varies from 3 to 10 min. Steam explosion can produce a relatively concentrated hemicellulose sugar stream from the pretreatment hydrolysate when the washing water is limited to the minimum (e.g., less than two times the biomass solids). Just like dilute acid pretreatment, steam explosion has a relatively low hemicellulose recovery of about 65% (Lynd 1996). The scalability of the process has not yet been addressed for commercialization.

15.6.2.2 Organosolv Pretreatment

The development of organosolv pretreatment technology is directly related to organosolv pulping (Kleinert 1974; Aziz and Sarkanen 1989; Paszner and Cho 1989). The chemistry of organosolv pulping is fairly well understood (McDonough 1993). Early work using organosolv pretreatment for fermentable sugar production was mostly conducted in the 1980s, with some success (Holtzapple and Humphrey 1984; Chum et al. 1988). The ethanol organosolv process was originally designed to produce clean biofuel for gas turbine combustors and was further developed into the Alcell® process for pulp production from hardwood (Williamson 1988; Pye and Lora 1991; Stockburger 1993). Ethanol is now the preferred solvent in organosolv process for biomass fractionation and pretreatment (Pan et al. 2005). The main advantages of the ethanol organosolv process are that 1) it can be directly applied to wood chips to produce a readily digestible cellulose substrate from almost all kinds of feedstock, including softwood and hardwood (Pan et al. 2005, 2006), therefore it eliminated the need for wood size reduction, and 2) it also produces very high purity and quality lignin with the potential of high-value applications (Kadla et al. 2002). Typical pretreatment conditions for woody biomass are temperatures of 175–195°C, pretreatment time around 60 min, ethanol concentration in pretreatment liquor of 50%, pretreatment liquor pH 2–3, and liquid to biomass solid ratio of 4–7. In pretreating poplar wood (Pan et al. 2006), about 70% of the lignin was removed from the substrate and recovered as high-purity lignin. Approximately 80% of the xylan was separated from the substrate, with 50% recovered as monomeric xylose in the soluble stream. About 88% of the glucan was retained in the substrate, and almost all of it was converted to glucose. Despite the excellent cellulose conversion, the xylose recovery rate was low. Furthermore, the relatively high liquor-to-solid ratio used in pretreatment produces a lower hemicellulose sugar concentration in the pretreatment hydrolysate. It also increases thermal energy consumption in pretreatment. Because the recovery of solvent ethanol is also expensive, the organosolv process is expensive.
15.6.2.3 Sulfite Pretreatment—SPORL

The recently developed SPORL process (Wang et al. 2009; Zhu et al. 2009) is based on the fundamental understanding of sulfite wood pulping. The degrees of hemicellulose dissolution, cellulose depolymerization, and lignin sulfonation and condensation are controllable by varying pulping conditions, such as temperature and pH (Yorston 1942; Hall and Stockman 1958; Bryce 1980). By properly controlling reaction temperature, pH, and time, lignocellulose recalcitrance can be removed through a mild sulfite pretreatment process.

A schematic process flow diagram of the SPORL is shown in Figure 15.5. Wood chips first react with a solution of sodium bisulfite (or calcium or magnesium or other bisulfite) at 160–190°C and pH 2–5 for about 30 min and then are fiberized using a disk refiner to generate fibrous substrate for subsequent saccharification and fermentation. The removal of the recalcitrance of lignocellulose by SPORL is achieved by the combined effect of dissolution of hemicelluloses, depolymerization of cellulose, partial delignification (less than 30%), sulfonation of lignin, and increasing surface area by defiberization through disk refining. Lignin sulfonation increased the hydrophilicity of SPORL-pretreated substrates and may have promoted the enzyme processes. The pretreatment liquor to biomass ratio is typically in a range of 2–3, significantly lower than that used in dilute acid and organosolv processes. Therefore, SPORL can produce a relatively concentrated hemicellulose sugar stream. The dissolved hemicellulose stream (a mixture of hexoses and pentoses) can be further fermented to ethanol. The fermentation of spent sulfite pulping liquor (SSL) has been in industrial practice for commercial cellulosic ethanol production for decades (Helle et al. 2008). The dissolved lignin sulfonate or five-carbon hemicellulose sugars can be used to produce value-added co-products that can be directly marketed and have been practiced in the industry. Therefore, SPORL has the advantage of valuable co-product commercial pathways from dissolved hemicellulose sugars and lignin, important to the economics of the process.

Typical pretreatment conditions of SPORL are temperatures of 170–190°C and pH 2–5. For laboratory batch operation, retention time is about 30 min. The bisulfite charge on biomass depends on the

FIGURE 15.5 A schematic process flow diagram of the SPORL.
feedstock species. For example, bisulfite of about 8% is required for softwood, whereas only 2–4% is required for hardwood. Cellulose-to-glucose conversion over 90% can be easily achieved even for softwood with low enzyme loading. The pretreatment is directly applied to wood chips without further size reduction. Furthermore, size-reduction energy consumption after pretreatment was only 20–50 Wh/kg oven-dried wood (Zhu et al. 2009; Zhu et al. 2010). With excellent cellulose conversion and very low size-reduction energy consumption, SPORL fits the requirement for forest biomass conversion. SPORL

![Comparison of enzymatic hydrolysis cellulose conversion and glucose yield between sulfite pretreatment to overcome recalcitrance of lignocellulose (SPORL) and the organosolv processes: (a) softwood and (b) aspen.](image_url)

**FIGURE 15.6** Comparison of enzymatic hydrolysis cellulose conversion and glucose yield between sulfite pretreatment to overcome recalcitrance of lignocellulose (SPORL) and the organosolv processes: (a) softwood and (b) aspen.
also has low formation of hydroxymethylfurfural (HMF) and furfural, two of the main inhibitors to fermentation. The combined severity factor under optimal SPORL pretreatment conditions ranges from 1.3 to 1.7. When SPORL was applied to spruce, a softwood, under the conditions for optimal cellulose conversion (Zhu et al. 2009), HMF and furfural formation levels were about 7 and 3 mg/g oven-dried wood, respectively. This is an order of magnitude lower than the 50 and 25 mg/g produced using steam-catalyzed pretreatment when glucose yield was maximized at a combined severity factor between 3 and 3.4 (Larsson et al. 1999). SPORL has an overall glucose recovery of 93% from spruce. SPORL also has excellent hemicellulose recovery. Major saccharides—arabinose, galactose, xylose, and mannose—yields are about 56, 86, 76, and 88%, respectively, for spruce (Zhu et al. 2009).

Because ethanol organosolv pretreatment is the most robust process in terms of removing lignocellulose recalcitrance, Figure 3.6a and b compare cellulose conversion between SPORL and organosolv pretreated softwood (Zhu et al. 2009) and hardwood (Wang et al. 2009). Very similar enzymatic hydrolysis conditions were used (i.e., 2% solid consistency, enzyme loadings of about 20 FPU cellulase and 30 CBU β-glucosidase/g cellulose). SPORL effectively removed lignocellulose recalcitrance and achieved cellulose conversion rates that match those of ethanol organosolv pretreatment with equivalent glucose yield.

Because SPORL is developed based on a wood pulping process, it has excellent process scalability, which is one of the key challenges in commercialization of lignocellulosic ethanol technologies. Most processes have not been demonstrated at commercial scales. Capital equipment required for commercial demonstrations of steam explosion and organosolv processes does not exist. On the other hand, the pulp and paper industry has the capability of handling biomass on the scale of 1000 tons/day, equivalent to the scale of future cellulosic ethanol production of 10^8 L per year. The SPORL process can make full use of the capital equipment, process technologies, and human capital in the pulp and paper industry, which can significantly reduce technological and environmental barriers for commercialization. Specifically, a pulping digester can be used for the sulfite pretreatment, and a disk refiner can be used for size reduction after the pretreatment. Furthermore, fermentation of SSL is a mature technology and has been practiced in the pulp and paper industry for many decades. With the good performance of a newly developed yeast strain on SSL (Helle et al. 2004, 2008), the prospect of achieving good ethanol yield through fermenting SPORL pretreatment hydrolysate is excellent. Therefore, SPORL is one of the most promising pretreatment processes for lignocellulosic ethanol production from forest biomass.

15.7 CONCLUSIONS

Eucalyptus, Pinus, Populus, and other promising tree species have considerable current and potential use for bioenergy worldwide. Eucalyptus, the most widely planted hardwood with 19.6 million ha, has many bioenergy applications in Brazil, China, India, Australia, and other tropical to freeze-infrequent countries. In the next decade, genetic and genomics studies will likely identify most genes regulating heritable variation of biomass productivity and wood property traits in Eucalyptus. Pinus species have similar bioenergy potential worldwide, especially loblolly and slash pines in the southeastern United States and P. radiata in New Zealand, Chile, and other temperate countries. Populus species are very promising for temperate regions of North America, Europe, and Asia. Biotechnology may also enhance the bioenergy production and qualities of Pinus and Populus species. SPORL pretreatment of forest biomass from eucalypts, pines, poplars, and other species promises to increase bioethanol production efficiency.

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