Short Rotation Woody Crops for Industrial Applications

Maud Hinchee[1], Lauren Mullinax[1], Michael Cunningham[1], and Nathan Ramsey[1]
ArborGen, LLC

Summary.
Purpose-grown trees have the potential to be a significant portion of the bioenergy solution in the Southeastern United States. Trees are a biomass source with existing end-use markets and associated infrastructure and provide a "living inventory" with a variety of benefits over annually harvested energy crops. The economic feasibility of utilizing tree woody biomass is improved by increasing productivity through alternative silvicultural systems and improved genetics. Improved productivity will achieve the ultimate goal of producing large amounts of biomass in a short period of time within a close proximity to the processing facility. Biotechnology can be used to improve productivity by enhancing growth in native species or through genetic improvements that allow highly productive, non-native species to be grown in the United States. Traditional breeding and selection as well as the introduction of genes for improved growth and stress tolerance have been shown to achieve high growth rates and improve site adaptability in *Populus* species. Several growth genes have achieved growth improvements of 20 to 40% in *Populus* through a variety of mechanisms. Traditional breeding and biotech gene insertion along with a tissue culture production process called somatic embryogenesis are being used to achieve growth improvements and reduce rotation times in Loblolly Pine. Growth increases that nearly double normal biomass production have been achieved through biotech gene insertion. A highly productive tropical Eucalyptus hybrid, *E. grandis* x *E. urophylla*, has also been improved through biotechnology. The introduction of a plant gene that improves freezing tolerance allows for survival at winter temperatures typically experienced in areas of the Southeastern United States while maintaining tree productivity. The yields achieved with Freeze-Tolerant Eucalyptus are predicted to meet or exceed those that have been defined by the DOE and others for the long-term feasibility of renewable energy production and meet delivered cost targets. Alternative management systems including high density plantings and coppice management further improve the economics for this hybrid.

Keywords.
Bioenergy, Purpose-Grown Trees, Populus, Eucalyptus, Biotechnology, Silviculture, Biomass Productivity

Woody biomass represents a renewable resource with multiple industrial applications. It serves as feedstock for the pulp and paper industry but also can be planted specifically to address the feedstock needs for the energy or biofuels industry. Trees and wood have been identified as part of the bioenergy solution in the "Billion Ton Report" (Perlack et al, 2005). This report investigated the feasibility of producing the estimated one billion dry tons of lignocellulosic biomass needed annually to meet the '30 x '30 goal for a 30 percent replacement of United States petroleum consumption with biofuels by 2030. In this report, trees grown for bioenergy applications were included under the heading of agricultural resources as part of the broadly defined 'perennial energy crops'. Purpose-grown trees are expected to account for 377 million

[1] ArborGen, LLC, P.O. Box 840001, Summerville, South Carolina 29484; telephone: 843-851-4129, email: mahinch@arborgen.com

dry tons of the 1.37 billion dry ton total biomass resource potential at projected yields of eight dry tons per acre per year (Perlack et al, 2005).

It is expected that Short Rotation Woody Crops, such as fast growing *Populus* species and hybrids, *Salix* species and hybrids, and *Eucalyptus* will be planted as purpose-grown wood on sites that enable high productivity and proximity to the processing plant.
Short rotation, purpose-grown trees have a variety of inherent logistical benefits and economic advantages relative to other lignocellulosic energy crops. Many of these advantages are driven by the fact that trees can typically be harvested year-round and continue growing year after year providing a 'living inventory' of available biomass.

Due to the flexibility associated with harvest time, trees have a reduced storage and inventory holding costs, and can minimize shrinkage or degradation losses typically associated with storage of annually harvested biomass. Since trees can be harvested after several years and at different times, tree biomass mitigates the risk of annual yield fluctuations due to drought, disease, pest pressures, as well as other biotic or abiotic stresses. This allows a better matching of biomass supply with demand. An excess supply of an annually-harvested crop is necessary to a hedge against years in which low yields are experienced in order to ensure full capacity utilization at a processing plant. Year-round harvest also allows for the distribution of harvest and transport activities throughout the year reducing infrastructure needs relative to annually harvested crops (Sims and Venturi, 2004).

Purpose-grown trees would minimize environmental impacts associated with biomass production since multi-year rotations of trees allow for extended periods with limited disturbance to the land. The multi-year rotation of trees also offers deployment and logistical benefits by reducing the footprint that must be planted and harvested each year. While the total acreage to feed a bioenergy plant may be similar between trees and other bioenergy crops with similar productivity, only a fraction of that total footprint for trees that would be planted or harvested in any given year (Table 1). Purpose-grown trees for biomass provide feedstock growers greater economic flexibility relative to other energy crops. The grower is provided a choice in harvest time and multiple end uses which include traditional forest products and energy products such as cellulosic ethanol and power generation through direct firing, co-firing, or wood pellet systems.

Table 1: Total and annual acreage needs for trees vs. annually-harvested energy crops

Feedstock	Biomass Needed (MM Green tons/year)	Productivity (green tons/acre/year)	Rotation Length (years)	Total Acres Needed (MM)	Acres Planted/Harvested Annually (MM)
Trees	100	20	6	5	0.83
Annually harvested crop	100	20	1	5	5

Genetics, Silviculture and Biotechnology Enable Short Rotation Trees

It has been projected by the DOE and others that a productivity rate of 8 to 10 dry tons per acre per year will be required for the long-term feasibility of renewable energy production (English et al, 2006). Research has been conducted on growing short-rotation trees for biomass production

for bioenergy in the United States and other countries (Short Rotation Forestry Handbook, 1995). Short-rotation coppicing of hardwoods offers the promise to produce biomass for bioenergy. Coppicing is the process by which new shoots and trees are regenerated from a cut stump following harvest. The use of coppiced hardwoods for this purpose is not novel although it is the subject of renewed interest and focused research (Andersson et al, 2002, Dickmann 2006). There are currently 12,000 acres of intensively managed short-rotation hardwoods. There are two main silvicultural systems: 1) moderately dense stands of cottonwood, and 2) dense stands with rotations of 1 to 4 years usually using Willows (*Salix* species) or Sycamore. Loblolly Pine and Sweetgum plantations are also being considered for bioenergy applications (Davis and Trettin, 2006; Dickmann, 2006).

However, the typical biomass productivity for these species is most likely not adequate to meet the demand cost-effectively. For example, short-rotation Willow crop yields range from 3 to 7 oven dry-tons per acre per year (Mead 2005). Sweetgum and Sycamore plantations grown for seven years on old agricultural land had, respectively, productivities of 1 and 2.3 oven-dry tons per year, although this is expected to increase later in the rotation (Davis and Trettin 2006). Populus (Eastern Cottonwood) planted on good sites can produce an average yield of 5 dry tons per acre per year. Loblolly pine grown to a 20 year rotation can produce an average four dry tons per acre per year (Mercker, 2007).

It is clear that productivity gains will require genetic and silvicultural research to address the required biomass yields for biofuel and bioenergy applications. However, without significant genetic improvement in the base growth rate of trees, the economics of a purpose-grown tree feedstock for energy may not be feasible. There are two basic strategies to achieve dramatic improvements in growth in plantation trees that involve biotechnology. The first is to genetically improve native trees to improve their productivity. The second strategy is to genetically improve a highly productive, non-native tree adapted so that it can grow in the United States.

Genetic Improvement of Native Species

<u>Populus</u>

Various *Populus* species and their hybrids are among the most rapidly growing trees adapted to temperate climates. Previous plantation establishment efforts have demonstrated rapid growth potential, but these plantings have also demonstrated that a high inherent growth potential is manifested only in the most favorable sites. The challenge is to determine how these high potential growth rates in specific genotypes can be demonstrated across a wide range of sites and environmental conditions. Unless strategies to increase productivity are employed together with tolerance to abiotic stress, plantations of these species or hybrids will remain limited.

Several different strategies offer potential to overcome these limitations and allow *Populus* to play an increasingly important role in bioenergy initiatives. The first and most straightforward of these strategies is through traditional breeding to generate hybrids and varieties that grow fast, have high volume increments, and can grow across a wide range of sites. For example, advanced *Populus* clones are being developed by companies such as ArborGen, LLC and Greenwood Resources (http://www.greenwoodresources.com) to have greater productivity and greater

adaptability. These programs typically consist of breeding among selected genotypes within a species or between species. The seedling progeny generated are then tested in a series of field trials. The first tests are in a nursery at close spacing to evaluate the genotypes for broad adaptability and resistance to various pests, which are then followed by one or more series of vegetatively propagated field trials in which the varieties are further screened for suitability to a wide range of sites. Commercial candidates are typically selected based on projected yields and wood properties after as many as 10 years of field testing.

In addition, the Oak Ridge National Laboratory, in conjunction with the Bioenergy Feedstock Development Program and Boise Cascade Corp., is developing methods to identify drought tolerant genotypes based on the presence of certain leaf metabolites (Oak Ridge National Laboratory, http://bioenergy.ornl.gov/papers/misc/drotpopl.html). These techniques could reduce the cost and improve the efficiency of breeding and selection of poplar varieties adapted to upland sites

The second approach involves direct genetic modification to add or modify genes that increase growth, increase stress tolerance, and improve adaptability. Research results strongly suggest that suboptimal nutrient and water availability limit *Populus* adaptability and productivity on many sites. Gene and gene families have been identified that have the ability to alter plant responses to water and nutrient limitations. Genes that are being tested in Populus include the *Populus tremula* and *Arabidopsis* SP-1 gene, as well genes involved in metabolic processes responsive to drought, redox proteins, transporter proteins, signal trandsduction proteins and transcription factors (Polle, et al, 2006).

A third approach would be to add genes to already widely adapted genotypes to improve their growth rate and productivity. Improved growth has been achieved in *Populus* through gene insertion technology. Genes involved in nitrogen metabolism such as glutamine synthetase (GS) and glutamate synthase (feredoxin-dependent GOGAT) (Zhong, et al 2004), produced growth improvements of 20-40% in transgenic *Populus*. Transgenic poplar characterized by overexpression of a pine cytosolic glutamine syntetase gene have exhibits other beneficial phenotypes including enhanced tolerance to water stress (El-Khatib et al, 2004), and enhanced nitrogen use efficiency (Man, et al, 2005). Genes involved in cell wall development have also affected tree growth. A β-1,4-endoglucanase (*cel*1) involved in cell wall modification during cell growth has improved growth in Populus (Shani, et al, 2004).

ArborGen is currently developing and testing Cottonwood trees that have growth improvement genes. Volume gain improvements of nearly 100 percent have been obtained in 3-year-old field trials of biotech Cottonwood (Figure 1).

Fig. 1 Eastern cottonwood (*Populus deltoides*) after three years of growth in an ArborGen field trial. The tree with the growth gene is the same genotype as the non-modified control.

With Growth Gene

Non-Modified Control

<u>Loblolly Pine</u>
Loblolly Pine (*Pinus taeda*), as a native North American species, has the advantage of wide adapatability across sites at less than 2,000 feet in elevation. Currently, it is the most widely planted forestry species in the world, with an average of 900 million seedlings planted annually in the Southeastern United States alone. Its wood, because of its lignin chemistry, is currently best suited for bioenergy applications that utilize direct firing or gasification technologies, although scientists believe that enzymatic processes might also be utilized (Frederick et al 2008). However, the economic limitation for Loblolly Pine in biofuel and bioenergy applications is its relatively long rotation time (15 years for pulp wood applications and 23 years for sawtimber applications).

To address this limitation, ArborGen has established a Loblolly genetic improvement program that utilizes advanced breeding and crossing methods to develop high-performing traditional seedlings that have improved growth, disease resistance and form. ArborGen has also utilized a tissue culture process called somatic embryogenesis to mass propagate selected elite Loblolly genotypes. Improvements in traditional breeding and selection are predicted to achieve 35 percent volume gains and sawtimber rotation times of approximately 20 years. Biotech gene insertion methods will be necessary to develop Loblolly with the productivity levels most desirable for bioenergy applications. Early research results indicate that rotation times of 15 years may be possible. ArborGen has introduced genes into loblolly pine that demonstrated nearly double the normal biomass production in the first three years of field trials. In Figure 2, the wood sample labeled "Improved" contains an ArborGen proprietary single gene to enhance growth. The control wood sample is from a tree of the same genotype as the tree with the growth gene.

Fig. 1 – Cross sections of Loblolly Pine after three years of growth in an ArborGen field trial. The sample labeled "Improved" contains a single gene to enhance growth. The control tree is the same genotype as the tree with the growth gene.

Eucalyptus

In Brazil, commonly planted Eucalyptus hybrids such as *E. grandis* x *E. urophylla*, routinely yield 10-12 dry tons per acre per year. A study with *E. grandis* in Florida indicated that this species could achieve total biomass productivity values exceeding 30 green tons (~15 dry tons) per acre per year, with the potential to reach 55 green tons per acre per year (Stricker et al, 2000). This scale of productivity addresses the biomass requirements for cost effective generation of bioenergy from lignocellulosic feedstocks. However, *Eucalyptus* species and hybrids with this level of productivity are adapted to growth in the tropics, and are killed or severely damaged by freezing temperatures. ArborGen has introduced a plant gene, which controls freeze tolerance in the model plant **Arabidopsis,** into a highly productive tropical Eucalyptus *E. grandis* x *E. urophylla* variety. The new variety, Freeze Tolerant Eucalyptus, has the potential to withstand 16º F or possibly even colder temperatures, while essentially maintaining its exceptional productivity (Fig. 3).

Fig. 7. A Eucalyptus hybrid, with or without the addition of a freeze tolerance gene, after a typical winter in the Southeast United States.

Non-Modified Control Eucalyptus, South Carolina

Freeze-Tolerant Eucalyptus, South Carolina

Freeze-Tolerant Eucalyptus (with green leaves) and Non-Modified Control Eucalyptus (with few leaves), Alabama

Therefore, the Freeze-Tolerant Eucalyptus variety is an ideal candidate for use as a short-rotation dedicated energy crop. High yields allow large volumes of biomass to be produced on a small land base close to the processing facility, minimizing transportation costs. The yields achievable with Freeze-Tolerant Eucalyptus are predicted to meet or exceed those that have been defined by DOE and others for the long-term feasibility of renewable energy production (i.e., 8 to 10 dry tons per acre per year (English et al, 2006). Total biomass-driven management systems could meet the delivered cost targets for bioenergy production. As with many other hardwood species, an added benefit of Freeze-Tolerant Eucalyptus is its ability to coppice when managed appropriately. Coppicing allows for subsequent crops without the added costs of establishment (site preparation, seedling and planting costs), which can provide a higher return to landowners. Coppice crops can show increases in productivity relative to the initial single-stem harvest (Sims et al, 2001), however, as with any other species, coppice yields will eventually decline. Re-planting will then become economically attractive as new varieties become available.

Improvements, like those discussed above, will be necessary to make forest trees a sustainable and economical feedstock option for the production of cellulosic ethanol and other forms of bioenergy. Table 2 summarizes the theoretical acreage needed to meet the “advanced biofuels” target in the 2007 Renewable Fuels Standard (RFS) in the Southeastern U.S. based on current productivity assumptions for Pine and *Eucalyptus* under pulpwood and high-density coppicing scenarios.

Table 2. Approximate total acreage needed to meet RFS in the US southeast using pine or *Eucalyptus*.

	Pine	*Eucalyptus*	
		Pulpwood management	Total biomass management
Productivity (green tons/acre/year)	7	20[b]	30[c]
Acres (million) needed to meet target 118 million green tons/year[a]	17	6	4

[a,b] ArborGen, unpublished data

[c] Estimated average over three coppice rotations (Sims et al, 2001)

Conclusions

The high productivity of purpose-grown short rotation trees, such as Freeze-Tolerant Eucalyptus, is expected to enable the economic feasibility of growing plantations for biofuels and bioenergy in the Southeastern United States. Bioenergy is already becoming a substantial market outlet for wood. According to TimberMart-South (2008), within the last 2 years, 16 new bioenergy projects were announced for the U.S. South, with an anticipated increase in wood consumption of 9 million green tons. The development of a bioenergy sector in the Southeastern U.S. holds great economic promise, and it is anticipated that purpose-grown short-rotation trees will be planted to address the 120 million green tons of biomass that will be needed annually as a feedstock for advanced biofuels. At an estimated price of $20 to $30 per green ton, this represents two to four

billion dollars in economic opportunity associated with biomass production for the Southeastern U.S. Upside demand exists with other bioenergy applications such as the production of electricity through direct burning of wood or co-firing with coal.

The inherent logistical benefits of trees in combination with the high productivity of new varieties of short-rotation trees, such as Freeze-Tolerant Eucalyptus, make it an ideal feedstock for traditional industrial end uses such as pulp and paper as well as various bioenergy conversion pathways ranging from cellulosic ethanol to electric power generation. Short-rotation trees will generate more wood on less land, requiring a smaller footprint to generate the necessary dry tons to feed industrial processing plants. This, in-turn, will lessen pressure to harvest from native and old growth forests in order to meet society's demand for pulp, paper and energy.

The choice of energy crops must also be adapted to regional conditions and needs, both in minimizing transportation costs as well as avoiding the current long-distance distribution limitations of ethanol. In the Southeastern U.S., where accessible inventory and harvesting infrastructure for forestry operations are already well established, trees provide a clear advantage for biomass production compared to annual crops. Although trees will play a significant role in helping to meet renewable energy standards, it is recognized that multiple, integrated approaches with a variety of different crop species and production systems will be required to meet our total renewable energy objectives.

References

Andersson, G.; Asikainen, A.; Bjorheden, R.; Hall, P.W.; Hudson, J.B.; Jirjis, R.; Mead, D.J.; Nurmi, J.; and Weetman, G.F. 2002. Production of forest energy. In: Richardson, J.; Bjorheden, R.; Hakkila, P.; Lowe, A.T.; and Smith, C.T. Bioenergy from sustainable forestry: Guiding principles and practice. Dordrecht, The Netherlands: Kluwer Academic Publishers: 49-123.

Cellulosic Biofuels Fact Sheet. (July, 2008) Environmental and Energy Study Institute. http://www.eesi.org/072308_Cellulosic_Biofuels

Davis, A. A.and Trettin, C. C. 2006. Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina. Biomass and Bioenergy. 30: 769-777.

Dickmann, D. L. 2006. Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. Biomass and Bioenergy. 30: 696-705.

DOE (2007**)** **"**DOE Selects Six Cellulosic Ethanol Plants for Up to $385 Million in Federal Funding**.,"** Press release: February 28, 2007. http://www.energy.gov/news/4827.htm

El-Khatib, R, EP Hamerlynck, F Gallardo, EG Kirby (2004) Transgenic poplar characterized by ectopic expression of a pine cytosolic glutamine synthetase gene exhibits enhanced tolerance to water stress. *Tree Physiology* 24, 729–736.

Energy Information Administration (2008) Renewable Energy Consumption and Electricity Preliminary 2007 Statistics. Energy Information Administration. United States Department of Energy, Washington, DC. http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/rea_prereport.html

English, B.C. De La Torre Ugarte, D.G. Jensen, K. Hellwinckel, C. Menard, J. Wilson, B. Roberts, R. Walsh, M. (2006) 25% Renewable Energy for the United States by 2025: Agricultural and Economic Impacts. University of Tennessee Agricultural Economics. http://www.25x25.org/storage/25x25/documents/RANDandUT/UT-EXECsummary25X25FINALFF.pdf

EPA (2005) US Environmental Protection Agency. Greenhouse gas mitigation potential in U.S. forestry and agriculture. EPA 430-R-05-006. Office of Atmosphere Programs, Washington, DC. http://www.epa.gov/sequestration/pdf/ghg_part1.pdf

EPA (2008) US Environmental Protection Agency. US Climate Policy and Actions. http://www.epa.gov/climatechange/policy/index.html Accessed August 19, 2008

Frederick, Jr. , W. J. S. J Lien, Ce. E Courchene, N.A. DeMartini, A.J. Ragauskas, K. Iisa (2008). Production of ethanol from carbhohydrates from loblolly pine: A technical and economic assessment. Bioresource Technology 99: 5051-5057

Man, Hui-min, R. Boriel, R. El-Khatib, E. G.Kirby (2005). Characterization of transgenic poplar with ectopic expression of pine cyotsolic glutamine synthetase under conditions of varying nitrogen availability. New Phytologist (167) 31-39.

Mead, D. J. 2005. Forests for energy and the role of planted trees. Critical reviews in plant sciences. 24: 407-421.

(Mercker, D. 2007. Short Rotation Woody Crops for Biofuels. University of Tennessee Agricultural Experiment Station. http://www.utextension.utk.edu/publications/spfiles/SP702-C.pdf)

Perlack, R.D. Wright, L.L. Turhollow, A.F. Graham, R.L. Stokes, B.J. Erbach, D.C. (2005) Biomass as a feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. US Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN

PEW (2008). Renewable Portfolio Standards (RPS). Pew Center on Global Climate Change. http://www.pewclimate.org/what_s_being_done/in_the_states/rps.cfm Accessed August 19, 2008

Polle, Andrea, A. Altman and X. Jiang (2006) Towards Genetic Engineering for Drought Tolerance in Trees. In: Tree Transgenesis Recent Developments, ed. Matthias Fladung and Dietrich Ewald. Springer Berlin Heidelberg.

Segrest, S.A. Rockwood, D.L. Stricker, J.A. Green, A.E.S. (1998) . *Energy crop yieldsfor Eucalyptus and cottonwood*, http://www.treepower.org/yields/main.html

Shani, Ziv, M. Dekel, G Tsabary, R. Goren and O. Shoseyov (2004) Growth enhancement of transgewnic poplar plants by over expression of Arbidopsis thaliana endo-1,4-β–glucanase (*cel*1). Molecular Breeding 14¨321-330.

Short Rotation Forestry Handbook (1995). University of Aberdeen. http://www.abdn.ac.uk/wsrg/srfhbook

Sims, R.E.H. 2001: Short rotation coppice tree. species selection for woody biomass. production in New Zealand. Biomass & Bioenergy, 20: 329-335.

Sims, R.E.H. Venturi, P. (2004) All year-round harvesting of short-rotation coppice *Eucalyptus* compared with the delivered costs of biomass from more conventional short season, harvesting systems. *Biomass and Bioenergy*. 26:27-37

Stricker, J.A., D.L. Rockwood, S.A. Segrest, G.R. Alker, G.M. Prine, D.R. Carter (2000) Short Rotation Woody Crops For Florida. University of Florida http://www.treepower.org/papers/strickerny.doc

TimberMart-South Market News Quarterly 2008 13:1 pg. 28. http://www.tmart-south.com/tmart/pdf/Qtr_01Q08news.pdf