Chapter 7

Woody Feedstocks - Management and Regional Differences

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Introduction

Rising concerns about long-term energy security, human health, global climate change, and a variety of other social and environmental concerns have combined to make developing renewable and sustainable alternatives to fossil fuels a critical national priority. Biomass, as a feedstock for renewable biofuels, bioproducts, and biopower, represents one such alternative, and one that has figured prominently in U.S. energy policy at both the national and state levels (Alavalapati et al. 2009; Aguilar and Saunders 2010; diversify). In addition to addressing the concerns listed above, the use of renewable biomass can help diversity products and markets for agriculture and forestry, create jobs, and promote rural development (Perez-Verdin et al. 2008; Openshaw 2009). Biomass can come from a variety of sources, including forests, agricultural crops, dedicated agriculture and forest energy crops, and various residue and waste streams. Woody biomass, in particular, is an underused resource with a great deal of potential. Although woody biomass can be recovered from a variety of waste and residue streams, emphasis has been placed on sourcing this material from forest management activities and the production of short rotation woody crops (SRWCs) on marginal land. The broad range of climate, soil and land use patterns across the United States means that a range of different forest management activities and SRWCs will be used to supply woody biomass in the years to come. The purpose of this paper is to survey the potential for forest biomass and several of the most promising and well-studied SRWCs across the United States.

Characteristics of Woody Biomass

Woody biomass has several characteristics that make it an appealing feedstock. Wood is harvestable year-round, has low mineral (ash) content (0.2-2.5 percent for most species, Klaas 1998), and a consistent energy (Miles et al. 1996) and sugar content. Short rotation woody crops, in particular, can supply a very uniform biomass feedstock supply of consistent quality because the entire system is managed starting with the selection of varieties to plant through to harvesting. Woody biomass can be harvested from multiple sources and can be mixed by end users, thus avoiding the seasonal harvest cycles and storage issues associated with many agricultural feedstocks. This ensures a consistent feedstock supply, lowers the risk of dramatic price fluctuations, and reduces the need for complicated and expensive long-term storage of material. However, large scale commercial systems for storing woody biomass have been developed by the wood products and pulp and paper industry and can be deployed as needed. The net energy ratios associated with biofuels, bioproducts and biopower from woody biomass are in the 10-20:1 range (Mann and Spath 1999; Keolian and Volk 2005). This means that considerably more energy is produced from these systems than is used in the form of fossil fuels to produce, harvest and deliver the

biomass and generate the end product. Because of their perennial nature, inputs to produce and harvest woody biomass from forests and short rotation woody crops are relatively small, which is a major factor in this positive energy balance.

Historical Use of Wood for Energy in the U.S.

Wood was the primary source of fuel in the United States before about 1830 (Fleming 1908 [as cited in Nash and Williamson 1972]). In 1880, wood was still a dominant fuel representing approximately 63 percent of the total U.S. energy consumption, but coal replaced wood as the primary U.S. energy source between 1880 and 1890 (Nash and Williamson 1972). Figure 1 shows U.S. energy consumption by source for 1635-2000. By 1949, wood accounted for approximately five percent of U.S. energy consumption, and by 2009, it accounted for approximately two percent of U.S. energy consumption (EIA 2010).

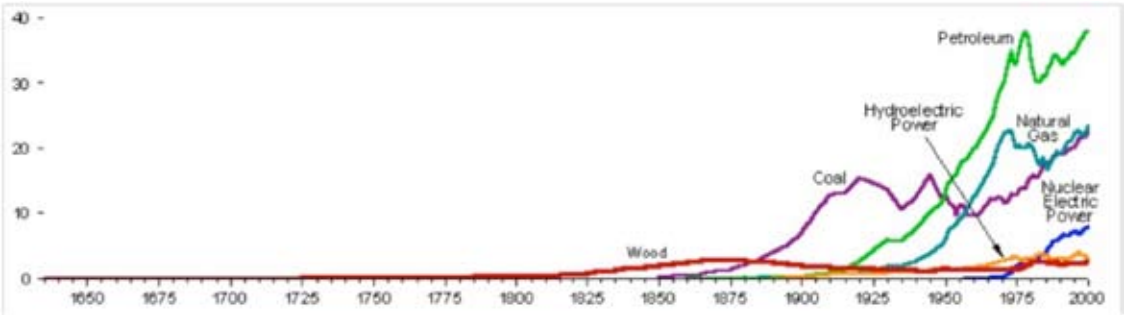

Figure 1: U.S. energy consumption by source, 1635-2000 (quadrillion btu) (EIA 2010).

The consumption of wood as a component of renewable energy is shown in Figure 2. From 1950 to 2010, wood, along with hydroelectricity, has consistently provided the bulk of renewable energy. In 2009 biomass was the largest source of renewable energy in the United States, providing 50 percent of the renewable energy consumed. Wood and biofuels provided 49 percent and 40 percent, respectively, of the biomass energy consumption in that year. (EIA 2010).

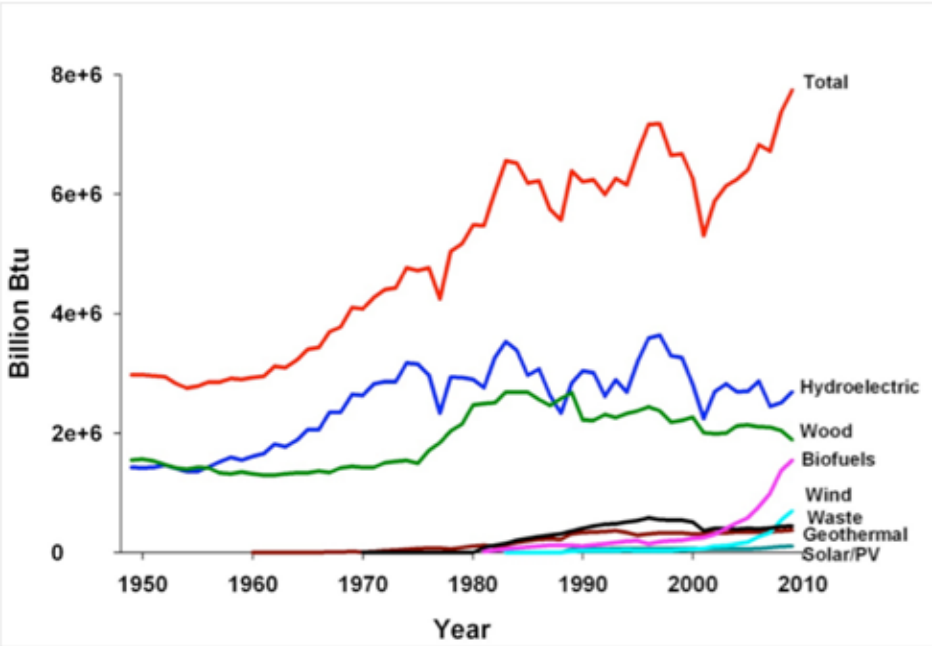

Figure 2: U.S. renewable energy consumption by source (billion btu) (EIA 2010).

Sources of Woody Biomass

Potential sources of woody biomass for energy include materials from both managed forests and SRWC systems. Materials derived from forest management include mill residues and pulping liquors, logging residues, wood from hazardous fuels reduction and forest health treatments, urban wood residues, and conventionally sourced wood (Perlack et al. 2005). Currently, wood used for energy is derived primarily from wastes and materials that are considered unsuitable for other products such as mill residues, pulping liquors, and fuelwood (low-quality wood harvested deliberately for energy production).

Mill residues can be classified into bark, chunks and slabs (course residues) and shavings and sawdust (fine residues). These residues are generally clean, reasonably uniform and dry, and often near existing facilities. While an excellent potential feedstock, much of these materials are in demand for current uses such as fuel in the form of chips or pellets, bedding, and mulch. Pulping liquors are waste products of the wood pulping industry and contain substantial amounts of energy. At this time, this material is used almost exclusively to produce heat and power for pulping and related processes. Urban wood wastes include all manner of discarded wood, yard wastes, and tree trimmings from the urban environment, and could be a potentially large source of energy feedstocks depending on the location, material, and costs (Biomass Research and Development Board 2008). A major challenge associated with urban wood waste is its inconsistent quality and supply.

Logging residues are classified as those materials remaining onsite or at the roadside following a conventional harvest operation, forest management activities, or land clearing. Wood from hazardous fuels or forest health treatments designed to reduce the risk of wildfire and/or losses to insect and disease also constitutes a potential source of wood energy feedstocks, as does wood removed from forest operations intended to restore, create, or maintain wildlife habitat, water quality, recreational opportunities or other ecosystem goods and services. Depending on market conditions and local objectives, conventionally sourced wood could also be used for energy production in some areas.

A range of SRWC systems are being developed across the country to meet the growing need for woody biomass, including eucalyptus, hybrid poplar, shrub willow and southern pine. Other species and systems are also being developed (such as sycamore and sweetgum), but the four listed above are the furthest along and will be the focus of this summary paper. There are research studies and some operational scale plantations of these species as energy feedstocks across the U.S., but large scale production of short rotation woody crops is not generally extant at this time. There are, however, more than 40 million acres of idle or surplus agricultural land available for the future deployment of woody energy crops in the United States (Graham 1994).

Results and Discussion

Estimates of Forest Biomass

There are over 208 million hectares (ha) of timberland (out of 751 million ha of forest land) in the United States with over 21 billion dry tonnes (odt) of aboveground woody biomass (Smith et al. 2009). Figure 3 illustrates the marked regional variation in standing forest biomass across the country. Each year, the amount of growth in these forests is 1.7 times greater than the amount of woody biomass that is being removed. In other words, the net growth to removal ratio across the country is 1.7. This ratio varies across the country from 1.2 in the south central region to 3.3 in the Pacific Northwest (Smith et al. 2009).

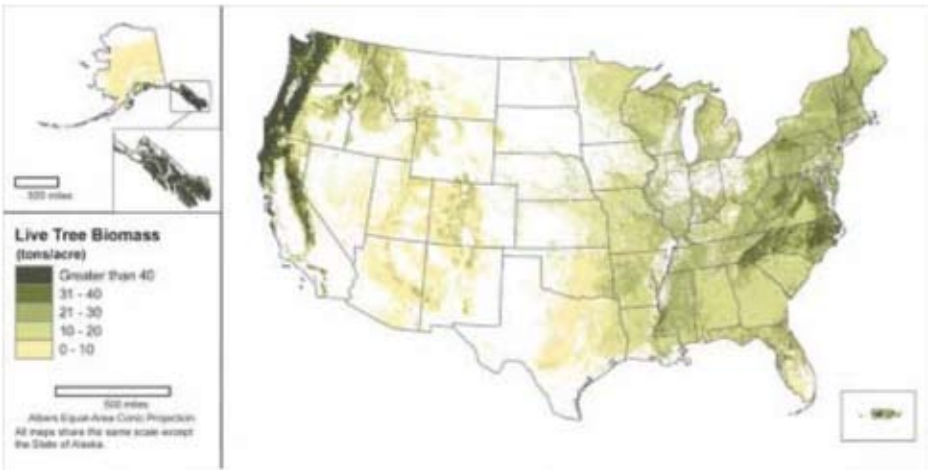

Figure 3: Live-tree biomass across the continental U.S. (tons/acre) (Smith et al. 2009).

In theory, one could harvest the annual surplus growth each year without diminishing the standing growing stock. In reality, however, there are many factors that reduce the amount of biomass that is actually available. In addition to there being a broad range of forest types across the country, silvicultural systems, demand for traditional woody products, land use, landowner attitudes, energy opportunities, and local and state policies vary across the country (Aguilar and Saunders 2010). Each of these factors affect the amount and type of biomass that could be made available (Benjamin et al. 2009; Butler et al. 2011, in press), as well as the cost of removing and utilizing that biomass. Policy factors also limit use. For example, the definition of 'renewable biomass' included in the Energy Independence and Security Act of 2007 (EISA, P.L. 110-140) limits the types of woody biomass from both private and public forests that can be made into biofuels eligible under the national Renewable Fuel Standard (RFS).

By estimating current uses and the magnitude of various reducing factors, a number of authors have estimated the supply of woody biomass that the nation's forest could yield on an annual basis. These include about 59 million odt yr^{-1} of logging residues (Miles and Smith 2009, Smith et al. 2009) and more than 44 million odt yr^{-1} from forest health and hazardous fuels reduction activities alone (Perlack el al. 2005). Estimates of the availability of pulpwood and other sources of conventionally-sourced wood for energy would vary substantially based on local conditions (Biomass Research and Development Board 2008, Conrad et al. 2010). In total, Perlack et al. (2005) estimated a potential supply of approximately 334 million odt yr^{-1} of forest wastes and residues.

Shrub Willows (Northeast, Midwest, Southeast)

Interest in shrub willows (*Salix* spp.) as a perennial energy crop for the production of biomass has developed in Europe and North America over the past few decades because of the multiple environmental and rural development benefits associated with their production and use (Börjesson 1999; Volk et al. 2004; Rowe et al. 2009). Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden and in the U.S. starting in 1986 (Volk et al. 2006). Since the initial trials in upstate NY in the mid-1980s, yield trials have been conducted or are underway in 15 states and six provinces in Canada and over 400 ha of commercial scale willow biomass crops have been established.

Shrub willows have several characteristics that make them an ideal feedstock for biofuels, bioproducts and biopower: high yields that can be sustained on three to four year rotations, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and good chemical composition and energy content (three year old willow stems averaged 19.4 MJ kg^{-1} [Miles et al. 1996] similar to other northern hardwood species).

The shrub willow cropping system (Figure 4) is designed to capitalize on several characteristics of shrub willows. It is built around planting genetically improved varieties on fully prepared open land with weed control and managing the crop as coppice using willow's ability to resprout. Willow can be grown successfully on marginal agricultural land across the Northeast, Midwest and parts of the Southeast United States. Weed control usually involves a combination of chemical and mechanical techniques and should begin in the fall before planting if the field contains perennial weeds, which is often the case with marginal land. It is essential to control this competing vegetation and prepare the soil before willows are planted in the spring. Trials incorporating cover crops such as winter rye (*Secale cereale* L.) to reduce erosion during establishment have been successful (Volk 2002). Initial trials using no tillage or conservation tillage techniques have shown some potential, but additional work with precision zone tillage equipment is needed to develop these techniques further. Willows are planted as unrooted dormant hardwood cuttings at about 15,000 plants ha^{-1} in the spring as early as the site is accessible using mechanized planters that are attached to farm tractors and operate at about 0.8 ha hr^{-1} (Figure 5). To facilitate the management and harvesting of the crop with agricultural machinery, willows are planted in a double-row system with 1.5 m between double-rows, 0.76 m between rows and 0.61 m between plants within the rows. Following the first year of growth, the willows are cut back close to the soil surface during the dormant season to force coppice regrowth, which increases the average number of stems per stool from 1-4 to 8-13 depending on the variety (Tharakan et al. 2005). After an additional three to four years of growth the stems are mechanically harvested during the dormant season after the willows have dropped their leaves. Forage harvesters with a specially designed cutting head cut the willow stems 5-10 cm above the ground, feed the stems into the forage harvester and produce uniform and consistent sized chips that can be collected and delivered directly to end users with no additional processing (Volk and Luzadis 2009). The chipped material is then delivered to end users for conversion to biopower and heat, biofuels and/or bioproducts. The plants will sprout again the following spring when they are typically fertilized with about 100 kg N ha^{-1} (Abrahamson et al. 2002; Adegbidi et al. 2003) of commercial fertilizer or organic sources like manure or biosolids. Further research is underway to refine fertilizer recommendations for new willow varieties across a range of sites. The willows are allowed to grow for another three to four year rotation before they are harvested again. Projections indicate that the crop can be maintained for seven rotations before the rows of willow stools begin to expand to the point that harvest equipment access is infeasible. At this point the crop can be replanted by killing the existing stools with herbicides after harvesting, chopping the stools with a heavy disk and/or grinding machine followed by planting that year or the following year.

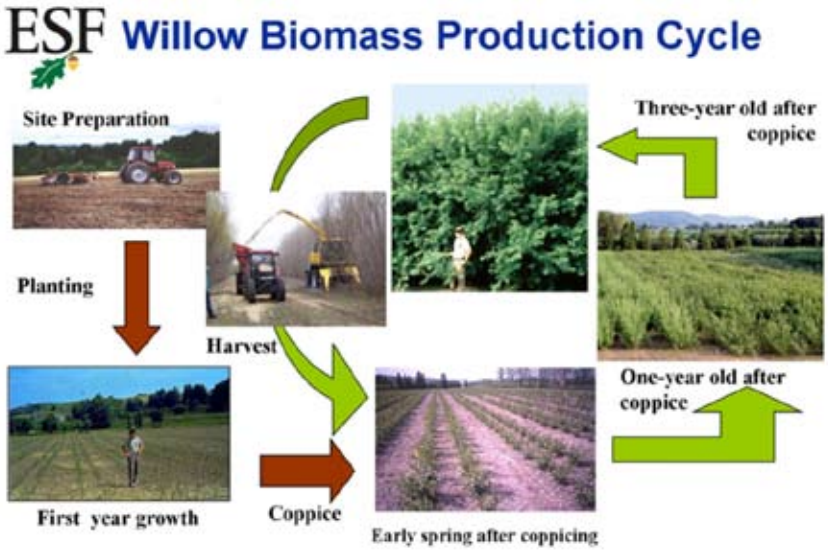

Figure 4: The willow biomass production cycle using current crop management recommendations. Site preparation is done in fall followed by planting in spring the next year. After one year of growth the crop is cut back to encourage vigorous shrub-like growth. After usually 3 to 4 years, the crop is ready to harvest. Then, a continuous harvest cycle of 3 to 4 years (the green cycle of arrows) is possible for more than 20 years without replanting the crop.

Rapid growth is one of the attributes that make shrub willows an appealing biomass crop (Figure 6). Yields from research plots of fertilized (Labrecque and Teodorescu 2003) and fertilized and irrigated (Adegbidi et al. 2001) unimproved varieties of willow grown for three years have exceeded 27 odt ha^{-1} yr^{-1}. Due to the costs associated with irrigation and the relatively low value for biomass, irrigation likely will not be used for most large-scale production operations, with the exception of situations where willow crops could be irrigated with wastewater as part of a nutrient management plan. However, these studies set a benchmark for the potential of shrub willow grown in this type of system, and higher yields will be possible with improved genetic material from breeding and selection programs. First-rotation, non-irrigated research-scale trials in central New York have produced yields of 8.4 to 11.6 odt ha^{-1} $yr.^{-1}$ (Adegbidi et al. 2001; Adegbidi et al. 2003, Volk and Luzadis 2009). Second rotation yields of the five best producing varieties in these trials increased by 18-62 per cent compared to first-rotations (Volk et al. 2001) and in subsequent rotations yields are maintained and largely dependent on weather conditions. The most recent yield trials using improved varieties of willow that have been bred and selected for biomass production at SUNY ESF are showing yield increases of 20-40 percent compared to unimproved standard varieties.

Figure 5. One year old sections of dormant stems are used to establish willow biomass crops using a planter that cuts the stems into 20cm long sections and pushes them into the soil.

Figure 6: Three year old willow biomass crops grown in upstate NY.

Several key bottlenecks in the willow crop production system have been overcome during the past few years making the deployment of willow biomass crops possible on a large scale. One of these barriers has been the availability of large quantities of shrub willow planting stock. Over the past few years a commercial nursery in western New York planted over 40 ha of willow nursery beds to meet the projected annual demand for millions of cuttings for planting stock and several other nurseries are being planned.

Another significant bottleneck in the willow biomass production system has been how to efficiently and economically harvest the crop and produce a consistent quality chip that is acceptable to end-users. Since 2004, Case New Holland (CNH) has been working with SUNY-ESF and other partners to develop a harvesting system for willow biomass crops based on a forage harvester fitted with a specially designed willow cutting head (Figure 7). Trials with this system indicate that for three or four year old willow biomass crops with the majority of stems <75mm in diameter, consistent high quality chips (>95 per cent of the chips being smaller than 37.5 mm) can be produced with the FR series NH forage harvester and NH FN130 woody crop cutting head at a rate of about 0.8-1.6 ha hr^{-1} (unpublished data).

These and other improvements in the system and the growing interest in using willow biomass for the production of biopower, biofuels and bioproducts are spurring large scale deployment. In addition to yield trials and small demonstration plots in 15 different states, over 500 ha of willow biomass crops have been planted in the Northeast and Midwest at a commercial scale. Other projects to deploy large areas of willow biomass crops are being developed in association with public and private entities as well as in Eastern Canada.

Figure 7. Harvesting willow biomass crops with a single pass cut and chip harvester in the dormant season using a system based on a New Holland forage harvester and a specially designed New Holland cutting head.

The economics of willow biomass crops have been analyzed using a cash flow model (EcoWillow v.1.2 (Beta) that is publically available from SUNY ESF (Buchholz and Volk 2011). The model incorporates all the stages of willow crop production from site preparation and planting through to harvesting over multiple rotations, and transportation of harvested chips to an end user. The removal of the stools once the crop has expired at the end of seven rotations is also included in the model. The cash flow model is designed based on experience establishing and maintaining over 200 ha of willow biomass crops in Upstate New York. The model is flexible enough so it can be applied across the range of sites where shrub willow might be grown. Users can vary input variables and calculate cash flow and profits throughout the entire production chain from site preparation and crop establishment to the delivery of wood chips to an end user.

For the base case scenario in EcoWillow, the internal rate of return (IRR) of willow biomass crops over seven three year harvest cycles (22 years) is 5.5 percent (Buchholz and Volk 2011) and the payback is reached in the 13th year with the revenues from the third harvest neutralizing the project's expenses. Harvesting, establishment, and land rent are the main expenses associated with willow biomass crops over their entire lifespan making up 32, 23, and 16 percent of the total undiscounted costs. The remaining costs including crop removal, administrative costs and fertilizer applications account for about 29 percent of the total costs of the project.

Projects are underway to reduce harvesting costs by improving the operation of the cut and chip harvesting system, based on a Case New Holland forage harvester, and optimizing the system to minimize the harvester's unproductive time spent turning around at the end of rows and waiting for wagons to line up to collect chips. Another approach is to reduce the frequency of harvesting operations. Increasing the rotation length from three to four years reduces harvesting costs by 14 percent and increases the IRR by 11 percent (from 5.5 to 6.2 percent).

Establishment costs are the second largest cost in the willow biomass crop production system, accounting for 23% of the total cost. Over 63 percent of these costs are for planting stock, so decreasing this input cost will affect the overall economics of the system. For instance, decreasing costs from a \$0.12 to \$0.10 per cutting reduces establishment costs by \$263 ha^{-1} and increased the IRR of the system from 5.5 to 6.5 percent. In addition, work is underway to quantify the trade-offs between lower per-acre establishment costs and potentially reduced yields resulting from reducing initial planting density.

Several other components of the system need to be developed to improve the overall economics of willow biomass crop systems and one of the main ones is yield. Increasing yields from the base case of 12 odt ha^{-1} yr^{-1} by 50 percent to 18 odt ha^{-1} yr^{-1} increases the IRR from 5.5 percent to 14.6 percent. With ongoing breeding and selection as well as efforts to improve crop management these levels of yield increases should be attainable in the near future.

Willow biomass cropping systems are in their infancy and there is potential for large gains by improving production practices and through breeding. By addressing the components of the system that have the greatest influence on costs, the overall economics of these systems can be improved so they can be deployed across the landscape. As the knowledge base about how willow grows and the roles it plays across the landscape expands, it will be deployed more effectively so that other benefits derived from this system, in addition to biomass, can be optimized.

Willow biomass crops are being developed as sustainable systems that simultaneously produce a suite of ecological and environmental benefits in addition to providing renewable feedstock for bioproducts and bioenergy (Volk et al. 2004; Rowe et al. 2009). The perennial nature and extensive fine-root system of willow crops reduces soil erosion and non-point source pollution relative to annual crops, promotes stable nutrient cycling, and enhances soil carbon storage in roots and the soil (Ranney and Mann 1994; Aronsson et al. 2000; Tolbert et al. 2002; Ulzen-Appiah 2002). In addition, the crop is constantly in its rapid juvenile growth stage, so the demand for nutrients is high, resulting in very low leaching rates of nitrogen even when rates of applications exceed what is needed for plant growth (Mortensen et al. 1998; Adegbidi 1999; Aronsson et al. 2000). The period with the greatest potential for soil erosion and nonpoint source pollution is during the first 1.5 years of establishment of the crop when cover is often limited because weeds need to be controlled and the willow canopy has not closed. The use of a winter rye cover crop has proven to be effective at providing cover for the soil without impeding the establishment of the willow crop (Volk 2002). Since herbicides are only used to control weed competition during the establishment phase of willow biomass crops, the amount of herbicides applied per hectare is about 10 per cent of that used in a typical corn-alfalfa rotation in upstate New York.

Birds are one indicator of the biodiversity supported by willow biomass crops that have been studied in the United States. A study of bird diversity in willow biomass crops over several years found that these systems provide good foraging and nesting habitat for a diverse array of bird species (Dhondt et al. 2007). Thirty-nine different species made regular use of the willow crops and 21 of these species nested in them. The study found that diversity increased as the age of the willows and the size of the plantings increased, and that birds have preferences for some varieties of willow over others (Dhondt et al. 2004). The number of bird species supported in willow biomass crops was similar to natural ecosystems, such as early succession habitats and intact eastern deciduous forest natural ecosystems. A similar study in the United Kingdom found total abundance of butterflies to be 132 percent greater in willow fields as compared to arable crop fields (Haughton et al. 2009). Instead of creating monocultures with a limited diversity across the landscape, deploying willow biomass crops will increase diversity relative to open agricultural land or arable crop fields.

Life cycle analysis of willow biomass crops has shown that they are low carbon fuels because the amount of CO_2 taken up and fixed by the crop during photosynthesis is almost equal to the amount of CO_2 that is released during the production, harvest, transportation and conversion of the biomass crop to renewable energy (Heller et al. 2003). The cycle is balanced for all the CO_2 inputs into the atmosphere from the system, because only the aboveground portion of the willow biomass crop is harvested and used in the conversion process. When willow biomass is used to offset fossil fuels, it can help reduce the amount of CO_2 emitted to the atmosphere. If the 40 million ha of available land in the U.S. were dedicated to the culture of willow or other SRWCs to offset coal use for power production, up to 76 per cent (0.30 Pg of C yr^{-1}) of the carbon offset targets for the U.S. under the Kyoto Protocol could be met (Tuskan and Walsh 2001).

The low inputs required by willow biomass crops relative to agricultural crops as well as their perennial nature results in a large, positive net energy ratio for the biomass that is produced. Accounting for all the energy inputs into the production system, starting with the nursery where the planting stock is grown through to the harvesting of biomass, converting it to chips and delivering it to the side of the field, results in a net energy ratio of 1:55 (Heller et al. 2003). This means that for every unit of nonrenewable fossil fuel energy used to grow and harvest willow, 55 units of energy are stored in the biomass itself. Replacing commercial N fertilizers, which are produced with large inputs of fossil fuels, with organic amendments, such as biosolids, can increase the net energy ratio to 73-80 (Heller et al. 2003). Transporting the woody biomass 40 km from the edge of the field to a coal plant where it is co-fired with coal to generate electricity results in a net energy ratio of 1:11. If a gasification conversion system is used, the net energy ratio is slightly higher (Keoleian and Volk 2005).

Hybrid Poplar (Midwest, Pacific Northwest)

Poplars (*Populus* spp.) are widely distributed worldwide and fossil records indicate that they were distributed throughout North America by 50 million years ago (Eckenwalder 1996). Today, the genus includes more than 20 species representing several taxonomic sections found throughout the northern hemisphere. Hybrids within and among species belonging to two sections, Aigeiros (cottonwoods) and Tacamahaca (balsam poplars), are of greatest commercial interest and are commonly referred to as "hybrid poplars."

Hybrid poplars grown under intensive silviculture have uses including saw-and veneer logs, fiber production for the pulp and paper industry, biofuels feedstock production, and phytoremediation. Large-scale commercial hybrid cottonwood plantations are a reality in Oregon and Minnesota for the production of sawn wood products, fiber and biomass for energy. Genotypes of eastern cottonwood (*P. deltoides* Bartr. ex Marsh) and hybrids between eastern cottonwood and Japanese poplar (*P. maximowiczii* A. Henry), European black poplar (*P. nigra* L.), and black cottonwood (*P. trichocarpa* Torr. & Gray) capable of producing in excess of 15 odt ha^{-1} yr^{-1} by age six have been identified in field tests even in the harsh climate of the North Central region of the United States (Riemenschneider et al. 2001).

Like willow, the unique ability of poplars to propagate vegetatively by adventitious rooting from hardwood cuttings has undoubtedly led to their commercial value and domestication as clones. The most economical means of plantation establishment is to plant dormant hardwood cuttings 22 to 35 cm in length (Heilman et al. 1994). The costs of nursery propagation are reduced and the productivity of the planting crew is high. Thus, just as vegetative propagation can confer significant genetic advantages through clonal propagation, vegetative reproduction offers significant cost reduction during commercial deployment.

In all cases, commercial programs in the United States rely upon high-yielding disease-resistant genotypes adapted to the region. These genotypes have been developed through breeding and field testing in the regions of commercial interest. Many possible breeding strategies can be applied to the development of a hybrid poplar woody biomass crop, but non-recurrent, first-generation inter-specific hybridization has been the predominant approach (Riemenschneider et al. 2001). Yet, all breeding strategies incorporate simultaneous selection for multiple traits through derivation of selection indices. A select variety, or genotype, must produce an adventitious rooting ability, rapid juvenile growth rate, be sufficiently resistant to various insect pests such that limited additional chemical measures can succeed in controlling the pest, and be sufficiently immune to various diseases so that the trees neither die nor have their growth significantly impacted. Rarely do we find a climatic region and species where all necessary attributes are possessed by a single species. Commercial genotypes in use today have most if not all of the important traits affecting production. However, the number of commercial genotypes in use today is relatively low and diversification, as well as yield improvement, is a goal of breeding programs.

Poplar can be managed in a number of ways depending on the desired end product and target rotation age. Plantations grown for the production of larger-diameter trees used in the manufacture of paper and lumber are typically planted at spacings ranging from 1680 trees ha^{-1} to 360 trees ha^{-1}. Plantations of this type are currently being managed commercially in Minnesota for pulpwood production and Oregon and Washington for a mix of products including saw timber and pulpwood. Poplar has the ability to resprout from established stumps after harvest and thus could be managed on repeated coppice rotations for biomass energy feedstock. Owing to the lack of interest in this type of management over the past decades, little additional research has been done on coppice systems due to the fact that the trees are small in diameter and, as such, use is likely restricted solely to energy. In light of the development of new genotypes and increased interest in dedicated energy production systems, the repeated coppice management option is a subject of renewed interest and field research is required to identify optimal plant densities, seasonality of coppicing, nutritional needs associated with repeated coppicing, stand protection owing to repeated coppicing and biomass harvesting systems.

Harvesting of poplar plantations can be accomplished using the same timber harvesting equipment suite found in standard forest pulpwood systems or can be accomplished by purpose-designed equipment that combines felling and chipping or bundling in a single machine. Selection of equipment and method of harvest depends on average tree size and age at harvest which are, in turn, determined by plantation density. A wide array of possibilities can be envisioned.

Yields from commercial plantations range from 10 odt ha^{-1} yr^{-1} in Minnesota to 20 odt ha^{-1} yr^{-1} in the Pacific Northwest. A series of large plot (10 x 10 tree square plots) yield trials conducted in Wisconsin, Minnesota, North and South Dakota from 1987 demonstrated yields as high as 11.0 odt ha^{-1} yr^{-1} by age 7 years (Netzer et al. 2002). Yields of newly selected genotypes in smaller plot experiments have exceeded 16.0 metric tons/hectare/year on good agricultural soil in southern Wisconsin (Riemenschneider et al. 2001). In current practice, sustainable average yields of 10, 13, and 20 odt ha^{-1} yr^{-1} have been achieved in the Midwestern, Southern, and Northwestern United States, respectively. With appropriate research and development investment, these yields can potentially be raised to 18, 27, and 40 odt ha^{-1} yr^{-1} for the same regions, respectively (personal communication, William Berguson, University of Minnesota; Brian Stanton, Greenwood Resources, Randy Rousseau, Mississippi State University). It is important to note that the research and development accomplishments will likely require the application of both classical breeding and field testing as well as discovery of new genetic technologies.

Factors affecting the sustainability of woody energy crops include soil fertility and erosion, water quality impacts and effects on biodiversity. In a summary paper on the subject published by Tolbert et al. (2000), several trends have been identified. Soil structure, total organic content and infiltration rate have been shown to improve under woody crops when compared to the agricultural system being replaced. Inputs of leaf litter and lack of annual site disturbance are thought to be contributing factors. Nutrient content and water yield of short rotation poplar plantations were found to be similar to older natural aspen stands in Minnesota. Increased soil carbon has been documented under short rotation systems particularly in those regions of the country where inherent soil organic content is low such as the South. Over the long term, soil carbon is expected to increase under perennial woody crops due to inputs of leaf and root biomass and lack of disturbance of the soil surface. Oxidation of carbon from upper soil layers has been shown to be a major factor accounting for differences between perennial energy crops and annually-tilled agricultural crops (Alder 2007).

The widespread natural range of eastern cottonwood, plus the possibility of extending the adaptive range by inter-specific hybridization, points to the fact that poplar is one of the most promising species groups for woody crops development nationally. High rates of biomass productivity, amenability to clonal propagation and agricultural management as well as coppicing ability are factors that make poplar a desirable crop to produce biomass for energy as well as other products. Past research has documented acceptable yields of these systems using genetic material that is essentially one generation away from native populations. Genetic improvement research underway in Minnesota and the Pacific Northwest has demonstrated significant gains in biomass yield and the benefits of a concerted breeding and field testing effort. Continued research in genetics and stand management is needed to improve yield and extend the range of high-yielding varieties to all regions where biomass crops may be planted.

Pine and Eucalyptus (Southeast)

The Southeastern United States has abundant land and forest resources, as well as a regionally distributed infrastructure in rural areas with potential for growing and processing biomass feedstocks for the production of biofuels and bioproducts. The region hosts a productive nexus of abundant and highly productive private land with a climate where sunshine and rainfall are plentiful, capable of supporting a variety of SRWC species. Literature suggests that leading SRWC candidate taxa are poplar, sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), eucalyptus (*Eucalyptus* spp.), and loblolly pine (*Pinus taeda* L). Black locust (*Robinia pseudoacacia* L.), silver maple (*Acer saccharinum* L.), and shrub willow have also been studied (Dickmann 2006). Loblolly pine and eucalyptus have gained considerable favor as likely purpose grown trees currently able to meet demands for wood, fiber, environmental benefits and energy.

In the southern United States, the forest products industry and forest plantations have a long and successful history. The change from relying on natural pine stands to establishing and intensively managing pine plantations for fiber production is one of the major success stories in the world for plantation forestry (Stanturf et al. 2003; Fox et al. 2007).

In 2007, estimates from the Forest Inventory & Analysis (FIA) data show more than 86 million ha of forestland in the South. Approximately 86 percent of southern forestland is privately owned (Butler 2008). Currently, 91 percent of the Nation's wood output is produced on private lands. In 2007, 95 percent of the forest in the South was classified as timberland (forest land available for and capable of wood production). Also, the region had more than 18 million ha in planted forests, which is 72 percent of all plantations and 71 percent of all planted timberland in the nation. Since 1982, more than 800 thousand ha have been planted annually, virtually all with native species. The South will likely continue its dominance as the nation's wood basket well into the future and this region's high yield planted forests will likely continue to play a crucial role in sustaining U.S. wood production (USFS 2010).

Purpose-grown wood, especially from trees grown through industrial forestry, is an excellent feedstock source for conversion into biofuels and bioproducts. The success of intensively grown pine forests in the South indicates plantations are economically viable under regional conditions of productivity, operational costs, and stumpage price. The dominance of private land ownership combined with an industrial presence strengthens the prospect to continue deploying purpose-grown plantations across the South.

Loblolly pine is the most economically important and widely cultivated timber species in the Southern United States (Figure 8). This tree is dominant on 30 million acres and comprises over half of the standing pine volume in the south (USFS 2007). This widespread cultivation as well as its high growth rates places loblolly pine in a likely position for SRWC culture (Dickmann 2006). The majority of pine planting stock is derived from tree improvement programs emphasizing superior growth rates, form class, and disease resistance - so genetic improvement of this species is highly advanced (Li et al. 1999; McKeand et al. 2003). The magnitude and productivity of existing loblolly plantations provides a standing biomass supply immediately capable of contributing to biofuels and bioproducts markets.

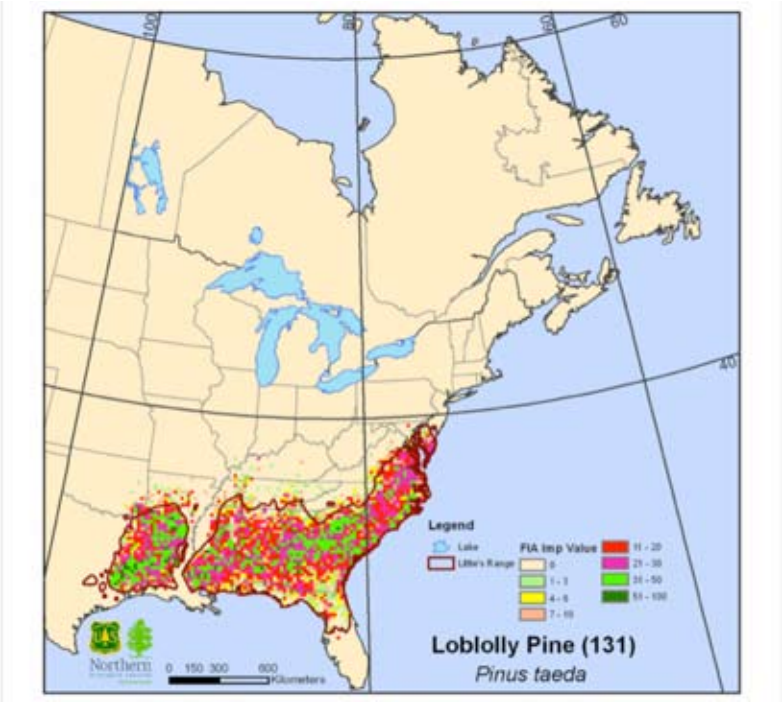

Figure 8: Range of loblolly pine (*Pinus taeda* L.) in the Southern United States. U.S. Forest Service.

Eucalyptus, one of the fastest-growing trees in the world, is an ideal candidate species for biofuels and bioenergy feedstock. Unlike the loblolly seedlings used in Southern forest plantations, eucalyptus can deploy a full canopy of leaves within the first 2 years and in 4 years can grow to 16 m in height, producing more than 32 odt ha^{-1} yr^{-1} under the right growing conditions (Gonzalez et al. 2010).

Figure 9: Eucalptus plantation (*Eucalyptus spp.*) in Florida, United States. ArborGen.

Eucalyptus is the most frequently planted fast-growing hardwood in the world, with an exceptional fiber that is in high demand for pulp and other bioproducts (Figure 9). Eucalyptus meets most of the desired features for a low-cost delivered biomass feedstocks, including the ability to grow more wood on less land (Gonzalez et al. 2009). Nearly 90 percent of U.S. forest landowners own less than 20 ha and the average parcel size is approximately 10 ha (Butler 2008). SRWCs would provide smaller land owners the opportunity to participate and economically benefit in biomass markets.

Recent species test indicate that two species, *E. benthamii* Maiden & Cambage var. *dorrigoensis* Blakely and E. *macarthurii* H. Deane & Maiden, appear to have enough cold tolerance to be considered for use in biomass plantations in the Southeastern United States. Cold-tolerant eucalyptus is currently growing at pilot scale in South Carolina, Florida, Alabama, Georgia and Texas. Wood production rates of 22 to 40 odt ha^{-1} yr^{-1} of total biomass are reasonable for the lower gulf coast region of the south. Eucalyptus biomass can be produced and delivered in the Southern United States at a competitive cost when compared to current biomass delivered costs of grasses and other hardwoods (Gonzalez et al. 2009; Gonzalas et al. 2010).

Forest production systems provide environmental services such as maintenance of hydrologic functions, soil conservation, and atmospheric CO_2 mitigation (Abrahamson et al. 1998). Environmental impacts of the establishment of SRWCs during the first year are not unlike those of the production of annual crops (Joslin and Schoenholtz 1997). SRWC plantations are expected to improve surface runoff and groundwater quality when compared to annual crops following the first establishment year (Thornton et al. 1998). Bioenergy produced from wood energy plantations could add substantially to energy security and be produced sustainably, with minimal adverse environmental effects.

The potential for SRWCs in the southeast is very good, provided that the operation is economical (Volk et al. 2006; Dougherty and Wright 2010). SRWC production costs are high relative to less intensive production systems and emphasize the need to maximize growth rates to lower unit costs. Although less productive sites may provide certain cost savings, they also have a lower yield potential (Gallagher et al. 2006). By initially selecting a good quality site and applying best management practices, intensive pine production can increase biomass yields efficiently, while maintaining or improving long term site productivity (Scott and Dean 2006; Allen et al. 2005).

The source of biomass feedstock should reflect what is locally available and grows well in the region. The practice of plantation forestry as a whole remains controversial to some (Cossalter and Pye-Smith 2003) despite its successful history in the South. Advancement of bioenergy will ultimately be determined by the availability of dedicated cropping systems designed for optimal performance from field production through conversion. Continued research in the arenas of production practices, fiber characteristics, and wood chemistry are strongly needed (Briggs 2010; Vance et al. 2010; Wegner et al. 2010).

The price of any biofuel or co-product use is the major factor determining the total amount of revenue to be divided among the members in the production chain. The single most important concept is that profit accrues to the most restricted resource in the production chain. Forest landowners will likely face two market strategies: 1) grow "traditional market species" (having a wide variety of uses) or 2) grow specialty species (specific properties for specific markets) where performance premiums could accrue. Supplementary markets in traditional forest products sectors provide landowners with flexibility. At the same time leveraging existing forest industry infrastructure provides additional cost savings. Landowners will ultimately benefit if markets develop.

Like other regions, however, a number of factors serve to reduce feedstock availability or increase costs of production or utilization. The Southern Forest Resource Assessment suggests that urbanization will have the greatest impact on the health and extent of southern forests (Wear and Greis 2002). As population density approaches 1 person per 1.7 ha the probability of sustainable timber production approaches zero (Wear et al. 1999). Conditions in land markets (development) and land costs influence forestland values, which in turn dominates the economics of growing biomass. Harvesting, transportation, and storage may double the cost at the conversion facility (Alig and Platinga 2004). To date there has been no decline in timber availability because the loss of forestland to urbanization has been more than offset by the increased productivity of pine plantations and the conversion of marginal agricultural land to forest (Wear et al. 2007). Some argue that increased revenue to landowners would aid in slowing urbanization. Increased valuation of rural production leads to increased valuation of the land. As property values increase, urban sprawl and fragmentation of the landscape decreases (Aronow et al. 2004).

All Southern states have financial incentives promoting bioenergy (Alavalapati et al. 2009). The findings of Conrad et al. (2010) suggest that the southern wood supply chain is in position to take advantage of a wood-energy market. Nearly all respondents reported that their clients are willing to sell timber to energy facilities, and no respondents reported that their clients would not sell to an energy facility. Secondly, nearly all foresters in this study reported that they do not have adequate markets for timber. In order for the forest products and biomass industries to be successful they require harvesting contractors to harvest and deliver wood to their facilities. The long term outlook for southern logging capacity, however, is unclear. (Conrad et al. 2010).

The structure of a mature cellulosic feedstock production and delivery system remains to be determined. Every parcel of private forest in the South is currently used or held for some purpose. If it is to be used to produce biomass feedstock, sufficient revenue will be required to outbid existing uses. If the lowest cost feedstock is a SRWC with a year round stand life and harvest window, markets may drive the structure to vertical integration. As the industry matures, feedstock production, harvest, and transportation will likely be centrally managed mirroring the historical structure of the Southern U.S. wood production industry. Integrated supply chains are not likely to develop without sufficient revenue and market alliances benefiting both buyers and sellers.

Conclusions

Forest biomass and SRWC have enormous potential to improve the long-term success and sustainability of our national energy systems, by providing secure, renewable, and low-carbon sources of transportation fuels, heat, electricity, and products. In addition, markets for these products can provide jobs, bolster markets, and provide much-needed economic outlets in the rural United States. Relative to traditional agricultural crops or open lands, ecosystems dominated by woody species often have the potential to perform better on metrics of biodiversity, soil, and water conservation. For these reasons, woody biomass is often considered (and expected) to be a sustainable energy source. To this point, however, the term sustainable has largely been used to mean that cultivation and harvesting of biomass feedstocks do not *negatively* impact key ecosystem functions and services (Caputo 2009; Elliot 2010; Zabel 2010; Page-Dumroese 2010; Janowiak and Webster 2010). We have only begun to explore another side of sustainability - how biomass cultivation and harvesting can be actively integrated into the bigger picture of land management, serving as an important tool to be used in meeting a wide variety of objectives-including management for ecosystem goods and services, keeping working forest and agricultural lands working, maintenance of ecosystem functions, outdoor recreation, biodiversity conservation, ecological restoration and energy production. To make this happen, it is necessary to better understand how SRWC systems and removal of biomass during integrated forest operations impact the provision and delivery of the goods and services expected. We will need to develop decision-making tools that allow us to intelligently align the production and use of biomass with other existing ecological, social, and economic objectives (Benjamin et al. 2010). These tools will include such things as effective frameworks for developing and evaluating silvicultural alternatives (Long et al. 2010) and multi-criteria analysis tools (Buchholz et al. 2009). Using these tools, the production of energy feedstocks can be integrated into farm and forest operations that provide biodiversity, water quality, traditional and non-traditional products, and other ecosystem services, in addition to renewable energy products.

One area in need of further development is the role that short rotation woody crop systems (including, potentially, the management of natural forests on a coppice system) can play in the overall landscape while providing energy feedstocks. Short rotation woody crop systems can be strategically placed in a variety of landscapes to accomplish specific management goals. Examples can include designing SRWC into agricultural landscapes to protect and enhance water quality and provide more diverse habitats and wildlife corridors, locating SRWC systems to specifically accomplish phytoremediation goals (French et al. 2006; Rockwood et al. 2004), and incorporating SRWC systems into marginal environments to provide diversity and other goods and services (Harper et al. 2010).

To ensure that woody biomass supplies are both consistent and reliable they will need to be economically viable. Currently most of these systems are marginally viable or only viable when biomass for energy is a co-product harvested along with higher value solid wood products. Additional research and development needs to be done to reduce the costs of harvesting, handling and transportation of woody biomass from forests. In SRWC systems the main factors driving the economics of the system are yields and establishment and harvesting costs (Buchholz and Volk 2011). The potential to increase yields dramatically in the near future with focused genetics and breeding and selection programs is large because relatively little work has been done for woody biomass. Since most SRWC systems are in their infancy, there is the potential to improve production systems while reducing production costs. Improving the value of a tonne of woody biomass will also impact the overall economics of these systems. The development of a wood-based biorefinery (Amidon et al. 2008), where multiple high value product streams are produced from the same feedstock, will make this material more valuable and help to create economically viable systems.

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