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Biomass production for biofuels using agroforestry: potential for the North Central Region of the United States

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Abstract As demand for energy increases in the United States, alternative energy sources are being sought both domestically and abroad. Biofuels have been promoted as a major source of alternative energy, but sustainable supply of biomass still remains a major challenge. Agroforestry offers a potential way to integrate perennial woody bioenergy crops with traditional agricultural crops to satisfy energy demands without sacrificing food production in the North Central Region of the United States. We suggest shelterbelts, alley cropping and working riparian buffer strips as ideal candidates for biomass production in agroforestry settings in this region. In addition to satisfying domestic energy demands, these systems could also potentially increase water quality, sequester carbon, improve aesthetics, and provide critical wildlife habitat. However, obstacles to implementing agroforestry systems for biomass production, such as a competitive price structure and stable markets, must be overcome before large-scale adoption by landowners.

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Introduction

Heavy reliance on foreign fossil fuels has sparked an interest in domestic renewable energy sources in the United States. In 2003, the Biomass Research and Development Technical Committee (BRDTC), established by United States Congress in 2000, envisioned a goal of a 30% replacement of United States petroleum consumption with biofuels by 2030 (U.S. Department of Energy (USDOE) 2003). The Energy Independence and Security Act Renewable Fuels Standard 2 (EISA 2007) mandates that annual biofuels use nearly triple from the current 12 billion to 36 billion gallons per year (BGY) by 2022, with 21 BGY coming from advanced biofuels. Currently, petroleum products supply about 37% of United States energy consumption, while biomass (including wood, ethanol, and biodiesel) provides about 3% (Energy Information Administration (EIA) 2009). A study conducted by the United States Department of Energy and United States Department of Agriculture concluded that achieving this goal might be possible and suggested several ways to increase productivity including, the utilization of non-food residues (e.g. corn stover) for biofuel production and expanding the use of perennial non-food biomass crops on marginal lands (USDOE and

U.S. Department of Agriculture (USDA) 2005). However, these suggestions have some potentially negative consequences. The use of non-food residual biomass can decrease soil fertility, which decreases grain production if too much material is removed on an annual basis (Blanco-Canqui and Lal 2009). The utilization of current agricultural land for non-food crop production could reduce food production, potentially driving up prices for consumers and reducing the overall availability (Graham-Rowe 2011; Pimentel et al. 2009). Agroforestry, the intentional integration of annual and perennial crops on the farm, offers a way to sustainably maintain grain production and provide a source of biomass for energy as well. Of all of the common North American agroforestry practices (Garrett et al. 2009), shelterbelts, riparian buffer strips, and alley cropping appear to be the most promising for maximizing sustainable biomass production, without sacrificing grain production, in the North Central Region (defined as: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, South Dakota, Wisconsin). This region contains some of the most productive farmland in the world and production of biomass in this area is critical to accomplishing the goal of the BRDTC. Although none of these practices are currently widespread throughout the region, small scale examples exist that demonstrate potential biomass production benefits. The objectives of this paper are to (1) examine the biomass production potential of agroforestry systems, (2) discuss which type of agroforestry systems are best suited for biomass production, and (3) determine what type of land should be targeted for implementation of agroforestry for biomass production in the North Central Region.

Biomass production potential in agroforestry systems

Woody species grown for biomass typically include fast growing, early successional species such as poplar (*Populus* spp.), willow (*Salix* spp.), and silver maple (*Acer saccharinum*) (Table 1). These species are shade intolerant and have the ability to coppice when harvested. Results from individual studies indicates that biomass production is variable, ranging from 5.4 to 30 Mg ha^{-1} $year^{-1}$ in the North Central Region (Riemenschneider et al. 2001; Tufekcioglu et al. 2003; Geyer 2006; Goerndt and Mize 2008), but is comparable to the production of annual grain-based biofuel crops such as maize (7–9.7 Mg ha^{-1} $year^{-1}$) and sorghum (4.5 Mg ha^{-1} $year^{-1}$) (Tollenaar and Lee 2002; USDA 2010a, b). Poplar, willow, and silver maple can be established across a range of sites, but site does play an important role in biomass yield. Goerndt and Mize (2008) reported a strong site influence in their study of woody biomass potential on marginal farmlands in Iowa. Results indicated greater estimated biomass production of poplar clones "Crandon" (*Populus grandidentada* × *Populus alba*) and "Eugenii" (*Populus* × *canadensis*) and silver maple following 10 years of growth on upland sites compared to sloped or bottomland sites, but predicted yield was greater on bottomland sites until year 5 for Eugenii and year 9 for Crandon. In a similar study, utilizing the same three tree species on two site types (upland and bottomland) in central Iowa, estimated woody biomass was greater on bottomland sites following four years of growth for all three species (Delate et al. 2005).

Within alley cropped agroforestry systems, woody species are typically grown on a short rotation (<10 years) to limit competition among other crops as the trees mature (Reynolds et al. 2007). Rotation age can significantly influence annual yields for perennial woody biomass and should be taken under careful consideration when designing an agroforestry system. Unlike annual and herbaceous perennial biomass, woody biomass does not need to be harvested annually. Annual growth of woody biomass is usually estimated by average yield at a given age, often referred to as the mean annual increment (MAI). Compared to the annual growth of grain based and herbaceous perennial biomass, MAI of woody biomass is not constant over time (Fig. 1). In a study of poplar clone growth in Iowa, Minnesota, and Wisconsin, Riemenschneider et al. (2001) reported that MAI was still increasing at the time of harvest in year six. Maximum biomass production occurs when woody species are harvested at the peak of the MAI (Fig. 1). Goerndt and Mize (2008) reported a culmination of MAI at nine years of growth for the poplar clone Crandon (3.1 m × 1.8 m tree spacing), indicating a nine year harvest rotation would maximize biomass production for that particular site.

Non-woody species such as miscanthus (*Miscanthus* × *giganteus*) and switchgrass (*Panicum*

Table 1 Production of annual and perennial biomass species within the United States North Central Region

Species	Annual yield (Mg ha^{-1})	Rotation	Location	Citation
Agricultural crop				
Maize (*Zea mays*) grain	7–9	Annual	Illinois	Tollenaar and Lee (2002)
Maize grain	9.7	Annual	United States	USDA (2010a, b)
Sorghum (*Sorghum bicolor*) grain	4.5	Annual	United States	USDA (2010a, b)
Tree species				
Black locust (*Robinia pseudoacacia*)	7.3	Annual	Kansas	Geyer (2006)
Cottonwood (*Populus deltoides*)	5.4	Annual	Kansas	Geyer (2006)
Honey locust (*Gleditsia triacanthos*)	6.1	Annual	Kansas	Geyer (2006)
Poplar (*Populus*) clones				
7300501	16.8	5 years	Iowa	Riemenschneider et al. (2001)
80X00601	17.2	5 years	Wisconsin	Riemenschneider et al. (2001)
D121	6.8	5 years	Minnesota	Riemenschneider et al. (2001)
Eugenii	17.0	10 years	Iowa	Goerndt and Mize (2008)
Eugenii	5.4	7 years	Iowa	Tufekcioglu et al. (2003)
Crandon	30.0	10 years	Iowa	Goerndt and Mize (2008)
Silver maple (*Acer saccharinum*)	5.7	Annual	Kansas	Geyer (2006)
Silver maple	18.0	10 years	Iowa	Goerndt and Mize (2008)
Silver maple	8.4	4 years	Iowa	Schultz et al. (1995)
Willow (*Salix*) clones				
SX67	18.3	2 years	Minnesota	Thelemann et al. (2010)
9882-41	12.5	2 years	Minnesota	Thelemann et al. (2010)
Grass				
Miscanthus (*Miscanthus* × *giganteus*)	29.6	Annual	Illinois	Heaton et al. (2008)
Switchgrass (*Panicum virgatum*)	10.4	Annual	Illinois	Heaton et al. (2008)
Switchgrass	9.4	Annual	Illinois	Khanna et al. (2008)
Switchgrass	13.1–19.9	Annual	Iowa	Tufekcioglu et al. (2003)
Giant cane (*Arundinaria gigantea*)	6.8	5 years	Illinois	Schoonover, personal communication

virgatum) can also be used to produce biomass (Table 1). *Miscanthus* × *giganteus* is a sterile hybrid cross of *M. sinensis* and *M. sacchariflorus*, while switchgrass (*Panicum virgatum*) is a tallgrass prairie species native to North America. Both species are perennial, C_4-grasses that are well adapted to a variety of sites in the region. Biomass yields of up to 29.6 Mg ha^{-1} $year^{-1}$ have been reported for *Miscanthus* × *giganteus* in Illinois and up to 19.9 Mg ha^{-1} $year^{-1}$ for switchgrass in Iowa (Heaton et al. 2008). Similar to woody species, yield varies with soil type and management practices. For example, Khanna et al. (2008) reported switchgrass yield ranging from 3.4 to 15.1 Mg ha^{-1} among several studies using different agronomic practices across the Midwestern United States, while Tufekcioglu et al. (2003) reported a range from 13.1 to 19.9 Mg ha^{-1} in Iowa.

Agroforestry practices with the greatest potential for biomass production

Shelterbelts

Shelterbelt, or windbreak, systems require linear rows of evenly-spaced trees, typically anywhere from 150 to 300 m apart, across a landscape (Brandle et al. 2009). Normally, three or more rows of fast-growing

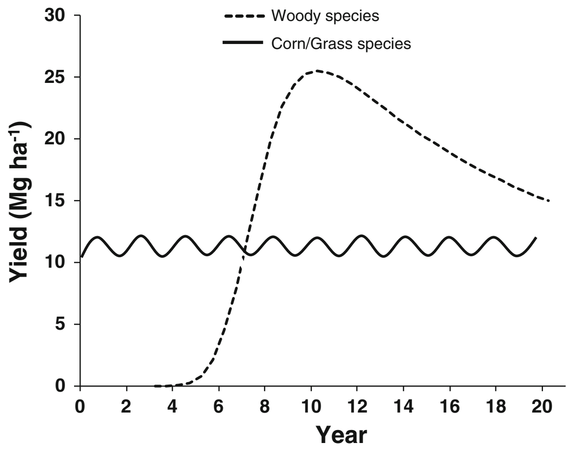


Fig. 1 Conceptual diagram of yield from a maize/grass species, which are harvested annually, and is relatively consistent over time and a tree species, which does not have to be harvested annually. Tree species yield will be maximized over a series of rotations if harvested at the peak of the yield curve

trees, and sometimes a row of shrubs as well, are established within each shelterbelt. In order to be effective, shelterbelts must be placed perpendicular to the prevailing winds because the primary function of shelterbelts is to reduce wind speed on the leeside. Reduced winds create a favorable microclimate for crop growth. Despite the loss of land required for the shelterbelt, the placement of shelterbelts can result in an overall increase in grain yield per hectare, particularly in years or locations where water is a limiting factor for crop growth (Brandle et al. 2009). In a shelterbelt study by Brandle et al. (1992), the authors established three systems in which 4.0, 5.4, and 9.1% of a 65 ha field was devoted to trees. In each system, crop yields per hectare increased following shelterbelt development, resulting in positive economic returns.

Despite the potential positive economic benefits, the inclusion of shelterbelt systems within the United States North Central Region is limited (Brandle et al. 2009). Nevertheless, this agroforestry practice should be considered when evaluating ways to increase perennial biomass production. In order for a shelterbelt system to be effective in both biomass production and increased crop yields, three to four tree rows within each shelterbelt would be necessary. Since shelterbelt effectiveness is a function of tree height, increased crop yields per hectare would disappear if the entire shelterbelt was harvested for biomass. Therefore, as one or two rows are harvested for biomass, and then replanted or allowed to coppice, the additional rows would be left in place as a shelterbelt until the previously harvested rows are tall enough to be an effective shelterbelt. Longer rotations would be necessary to ensure adequate tree height; however, this might actually increase perennial biomass production as most short-rotations of woody biomass occur before the culmination of the mean annual growth (Fig. 1; Riemenschneider et al. 2001; Goerndt and Mize 2008).

Riparian buffer strips

Riparian buffer strips involve the placement of perennial species between crop species and adjacent waterways (Schultz et al. 2009). Vegetation within buffer strips, typically 10–30 m in width, can include grasses, shrubs and trees, and this vegetation can significantly reduce nutrient and sediment runoff in agricultural systems (Schultz et al. 1995; Lee et al. 2003; Schoonover et al. 2005). Because agricultural runoff has been identified as a key contributor to nonpoint source water pollution, including the hypoxia in the Gulf of Mexico (Burkart and James 1999; Broussard and Turner 2009), riparian buffer strips are the most common, albeit heavily subsidized, agroforestry practice in the North Central Region. Federal sponsored programs such as the Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), Forest Stewardship Program, Wetlands Reserve Program, and Wildlife Habitat Incentives Program provide financial incentives to take land within highly erodible or riparian areas and plant perennial vegetation (riparian buffer strips) that reduce nonpoint source pollution. Although land within these programs is oftentimes used to grow perennial biomass species, harvesting of these crops is typically not allowed under some of these programs. While in the past farmers have been hesitant to take fertile agricultural land adjacent to waterways out of production without financial incentives, increased market values for woody biomass could potentially increase voluntary participation for establishing riparian buffer strips that would not have the harvest restriction of current government sponsored programs. Establishment of additional riparian buffer strips would take some land out of grain production, but these areas would likely yield the greatest amounts of perennial biomass given the fertile soils of riparian areas (Tufekcioglu et al. 2003; Goerndt and Mize 2008; Thelemann et al. 2010).

Alley cropping

Alley cropping involves planting rows of cultivated crops in between rows of trees (Garrett et al. 2009). In theory, greater yields can be gained by combining multiple crops (e.g. trees and maize) on one hectare than could be grown in separate monocultures on that same hectare (Jose et al. 2004). Although somewhat common in tropical regions, outside of research demonstrations, alley cropping has had limited adoption in the North Central Region. Most existing examples have used primarily high timber value species, such as black walnut (*Juglans nigra*). Although high value timber species can potentially provide greater long-term financial yields than traditional maize monocultures (Benjamin et al. 2000), these tree species are unlikely to be used for biomass production (Garrett et al. 2009). While there are several studies that have investigated short-term yields of annual crop and trees in alley cropping systems in the North Central Region (Miller and Pallardy 2001; Delate et al. 2005; Reynolds et al. 2007), review of existing literature did not reveal any published crop/biomass production estimates over a long-term period (series of multiple rotations for annual crops and biomass species) for these systems.

Limited research in temperate alley cropping systems does suggest that grain yields decrease in these systems as trees mature (Garrett et al. 2009). In a black walnut and maize alley cropping system in Indiana, the authors reported a 25% reduction in maize yield in alley cropped rows compared to maize yield in an adjacent monoculture in year 11 of the system (Gillespie et al. 2000). However, barrier and trenching treatments that physically separated maize rows from tree rows could maintain maize yields for a longer period (Gillespie et al. 2000; Miller and Pallardy 2001). Substitution of maize for cool season grasses or legumes may also help maintain biomass yields. Typically, cool season grasses and legumes species utilizing C_3 photosynthesis, are more shade tolerant than C_4 species.

In a study of several cool season grasses including orchardgrass (*Dactylis glomerata*), tall fescue (*Festuca arundinacea*) and clover (*Trifolium* spp.) in Missouri, Lin et al. (1999) reported minimal yield reductions under 50% shade. In addition to the potential decreased maize yields in alley cropped systems, alley cropping can take a significant portion of agricultural land out of maize production. In maize/poplar alley cropping system in southern Canada 13–16% of available land area was lost to tree production, while in a maize/silver maple alley cropping system in Missouri, 35% of available land area was used for trees (Miller and Pallardy 2001; Reynolds et al. 2007). Although the loss of maize production, from decreased yield due to tree competition and lost land area, could potentially be compensated for by woody biomass production, further research needs to be conducted across a broad range of site conditions to see if greater annual biomass production per hectare can be achieved in this system in the North Central Region.

Targeting lands for implementing agroforestry systems

Nearly 55% of the cropped area in the United States lies within the North Central Region and the area accounts for 85% of all maize production in the United States (USDA 2010a; Fig. 2). Biologically, production of perennial biomass within existing cropped areas of this region is ideal, but incorporating an agroforestry system for biomass production into the traditional agricultural model in this region is a challenging task that will require agricultural producers to overcome logistical, financial, and cultural obstacles. Many producers are reluctant to plant trees, and conversion to an agroforestry system is unlikely, or even appropriate, for all farmland. Taking biological and social constraints into consideration, we suggest that riparian marginal land is an ideal candidate for biomass production in an agroforestry system in this region. Oftentimes these areas retain water during the spring months making them poorly suited for annual agricultural production during wet years, but ideal for tree establishment and development (Groninger 2005; Thelemann et al. 2010). In addition, currently many of these areas are out of production because of participation in Federal programs such as CRP and EQIP, and biomass could be produced in these areas to meet the goals of the BRDTC and EISA without taking additional agricultural land out of production (Volk et al. 2004).

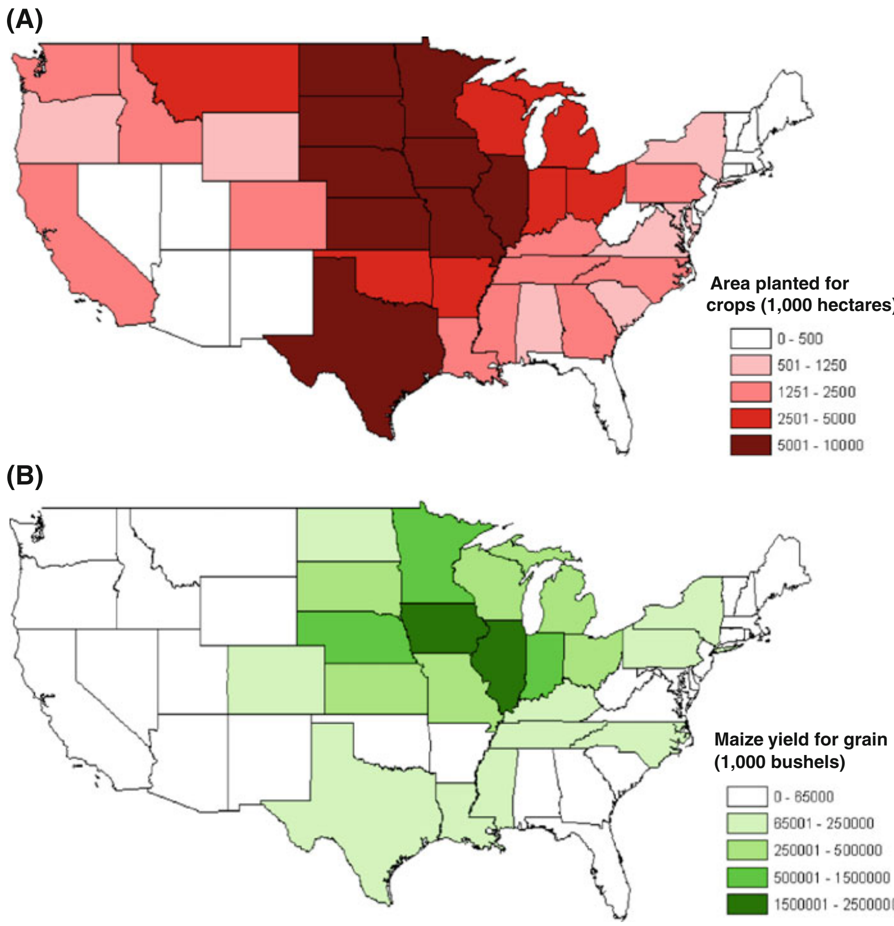
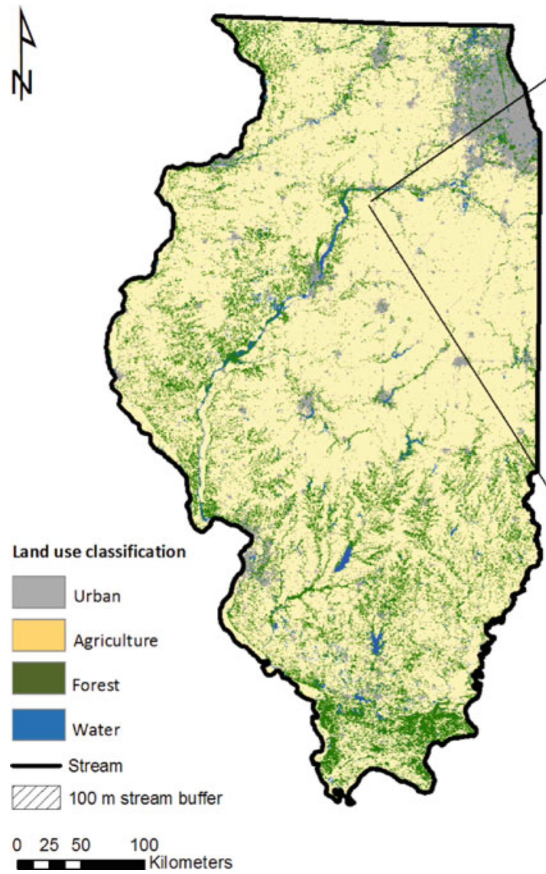


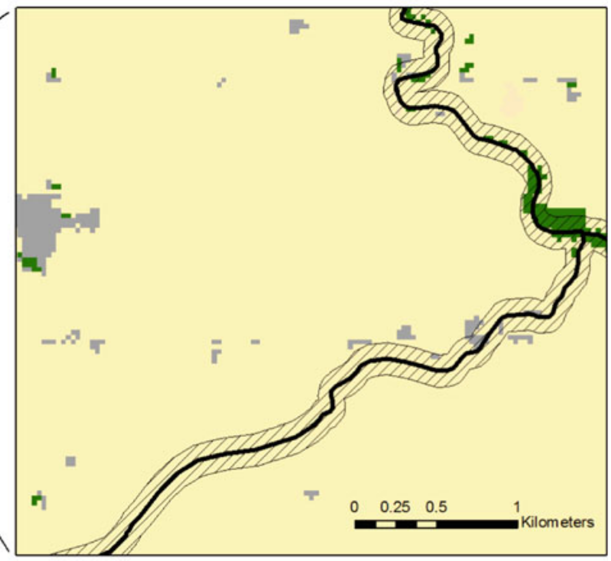
Fig. 2 Hectares in the United States devoted to maize production (**a**) and yield of maize grain by State (**b**) (USDA 2010a, b)

This would be more appealing to agricultural producers who may be reluctant to take land well-suited for an agroforestry system, such as shelterbelts on marginal uplands, given the current market for grain prices. If additional lands are required to meet production goals, riparian lands are also ideal because they are easily identifiable on the landscape and agroforestry systems for biomass production could be concentrated so that they would not interfere with traditional agricultural operations. For example, the state of Illinois is approximately 14,600,000 ha in size and nearly 77% of the area is classified as 'agriculture' (Fig. 3; IL NHS 2003). There are 131,700 km of streams and shorelines within the state (IL DNR 2004). A GIS overlay analysis of the land classification within a 100 m buffer of all streams and shorelines in Illinois estimated 3,490,000 ha of buffered land. Approximately 2,275,000 ha of this land within the riparian buffers was classified as agriculture, representing 20% of all available agriculture land that could potentially serve as a source of biomass. Within riparian areas we suggest establishing an alley cropping and working riparian buffer systems for biomass production. These systems would integrate rows of short rotation, high yielding woody crops with alleys of perennial/annual grasses or maize and allows for production of biomass without sacrificing grain production (Fig. 4).

Additional benefits of agroforestry systems established for biomass production

By targeting alley cropping and working riparian buffer systems in riparian areas, biomass could be generated while potentially providing additional benefits such as reduction of nonpoint stream pollution and sediment run off. In a long term study of water quality in the Mississippi River Basin, Broussard and Turner (2009) concluded that increased agricultural





Illinois land use classification according to Landsat imagery (IL NHS 2003).

Land classification	Illinois (ha)	100 m stream buffer (ha)
Agriculture[1]	11,158,220	2,275,340
Forests[2]	2,224,432	902,965
Urban[3]	944,829	156,097
Water	247,070	158,105
Total	14,574,551	3,492,507

[1]Agriculture – grain production and rural grasslands, [2]Forest – forests and wetlands, [3]Urban – developed land

Fig. 3 Land use classification of Illinois according to Landsat imagery (IL NHS 2003). Table indicates the amount of agricultural land within Illinois and 100 m of all streams and shorelines in Illinois

production has increased nitrate–N loading in hydrologic systems and that these levels could be reduced by increasing perennial crop cover, which an agroforestry system provides. This is supported by additional studies in this region (Lee et al. 2003; Schoonover et al. 2005). Schoonover et al. (2005) reported a 97% reduction of dissolved nitrate–N and 74% reduction of dissolved ammonium–N in surface runoff in a 10 m riparian forested buffer in Illinois. Lee et al. (2003) reported similar results of N reduction in a 16.3 m switchgrass/woody buffer in Iowa, as well as, a 97% reduction in sediment. One of the existing problems with riparian buffers is that over time they lose some of their effectiveness. Concentrated flow paths often develop that decrease the ability of the riparian buffer to filter surface runoff (Dosskey et al. 2002). Active management in an agroforestry biomass production system could prevent concentrated flowpaths from forming, thereby increasing the long-term sustainability of riparian buffers. Additional research is required, however, to determine the effects of biomass harvesting on other environmental benefits. It is unclear if the periodic removal of biomass will have an effect on the nutrient filtering capabilities of these systems. It is also unclear if maize production within the alleys would have an effect on the environmental benefits as well.

The Intergovernmental Panel on Climate Change states that the utilization of woody products for bioenergy is part of a global strategy to mitigate climate change (IPCC 2007). Agroforestry systems that incorporate perennial species have the ability to sequester carbon at a much greater rate than traditional agricultural crops (Schoeneberger 2009; Udawata and Jose 2011). For example, Tufekcioglu et al. (2003) reported significantly greater aboveground and belowground biomass for poplar and switchgrass compared

Fig. 4 Silver maple (*Acer saccharinum*)/forage mixture alley cropping system in central Iowa

to maize and soybeans (*Glycine max*) in central Iowa. Similar results were observed in southern Ontario tree-based alley cropping system (Peichl et al. 2006). Although the aboveground biomass in the proposed system would be harvested and used to provide energy, a reduction in overall CO_2 emissions would still occur because woody biomass production is considered C neutral (Heller et al. 2003) and displaces the amount of fossil fuels used (Volk et al. 2004; Satori et al. 2006).

In addition to improved water quality and carbon sequestration, alley cropping and working riparian bufferstrip systems also improve aesthetics and provide critical wildlife habitat in an otherwise oftentimes homogenous agricultural landscape. Recent research indicates a preference among rural residents for riparian tree buffers in Midwestern agricultural landscapes (Sullivan et al. 2004, Kenwick et al. 2009). In a study of riparian buffers, row crop fields, and pastures in central Iowa, Berges et al. (2010) found greater avian abundance, richness, and diversity in riparian buffer strips. These agroforestry systems can also provide critical wildlife corridors that can connect fragmented habitats on the landscape thereby helping area-sensitive faunal species. Increased wildlife abundance also provides additional opportunities for generating revenue through hunting leases for upland game that are more likely to utilize these areas (Grala et al. 2009).

Obstacles to implementation of agroforestry systems for biomass production

Agroforestry offers the opportunity to integrate annual and perennial biomass species on farms and within a landscape, increasing biomass production potential compared to single species production systems. It can also ensure the availability of biomass year-round by harvesting trees and crops at different times of the year. Currently, one of the major constraints to implementing agroforestry systems in the North Central Region is the increased complexity involved with trying to grow multiple species on the same tract of land. Thorough consideration must be given to the design and operation of these systems. Information is needed on site specific management practices (e.g. appropriate species combinations, optimal rotation lengths, width of alleys, etc.) that will maximize biomass production in these systems. Other constraints include lack of stable markets and a competitive price structure for perennial biomass crops. It is unlikely for agroforestry practices to become widely adopted unless agricultural producers can obtain a financial return for establishing and maintaining these systems that is at least similar to the value they can obtain from utilizing traditional agriculture practices (Matthews et al. 1993; Secchi et al. 2008). Currently, maize grain yields \$145 Mg^{-1}, but pulpwood yields are significantly lower, \$4–26 Mg^{-1} in Illinois (USDA 2010a; IL DNR 2009). While most likely long-term biomass production would be greater using perennial crops in riparian buffer strips (Table 1), value for maize more than offsets greater production of perennial biomass at current prices. Until the market values for perennial biomass increase, conversion of annual crops to perennial crops is unlikely, despite potential greater biomass production (Matthews et al. 1993). Even then, government incentives/assistance will most likely be necessary to overcome the risk and cost of establishing perennial species and encourage wide-spread transition to an agroforestry system. It is possible that funding could come from current government programs such as CRP that provide cost share assistance to establish perennial species and rental payments once the land is taken out of traditional production, but do not currently allow harvesting. In our proposed alley cropping and working riparian buffer systems, cost share assistance could be used to establish the perennial species, but rental payments could be eliminated over time because the land is kept in production, providing food, biomass, and environmental benefits in a working landscape.

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