Primer

Introducing perennial biomass crops into agricultural landscapes to address water quality challenges and provide other environmental services

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The world is faced with a difficult multiple challenge of meeting nutritional, energy, and other basic needs, under a limited land and water budget, of between 9 and 10 billion people in the next three decades, mitigating impacts of climate change, and making agricultural production resilient. More productivity is expected from agricultural lands, but intensification of production could further impact the integrity of our finite surface water and groundwater resources. Integrating perennial bioenergy crops in agricultural lands could provide biomass for biofuel and potential improvements on the sustainability of commodity crop production. This article provides an overview of ways in which research has shown that perennial bioenergy grasses and short rotation woody crops can be incorporated into agricultural production systems with reduced indirect land use change, while increasing water quality benefits. Current challenges and opportunities as well as future directions are also highlighted. © 2017 Wiley Periodicals, Inc.

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INTRODUCTION

Bioenergy or biofuel crops are plants that are cultivated primarily as energy sources for heat and electricity generation and for the production of liquid fuels for transportation. In developing countries, people in rural areas rely primarily on biofuels for their cooking, heating, and lighting energy needs.[1,2] Using biofuels makes economies less dependent on fossil fuel and can help slow down the rate of greenhouse gas (GHG) emissions. Biofuel crops use carbon dioxide (CO_2) during photosynthesis, therefore consuming energy derived from them should, in principle, not increase future atmospheric CO_2 levels compared to fossil fuel, and thereby help mitigate impacts of climate change.[3,4] The extent of this advantage is an area of current discussion. Large-scale biofuels production has also been controversially related to competition for land allocated for food and feed production, potential loss of biodiversity, and water quantity and quality impacts[5] as well as to potential conversion of forests and grasslands to replace croplands converted to bioenergy crops, with potential increase in GHG emissions over the long-term.[6] Globally, food production should increase by 70% to satisfy nutritional needs of approximately 9 billion people by 2050,[7] hence, the conversion of agricultural land to produce non-food crops is undesirable. Currently, the majority of worldwide biofuel production comes as ethanol from first generation biofuel crops including corn in the United States, [8,9] sugarcane in Brazil, and wheat and sugarbeet in Europe.[10–12] However, the research community is now focusing on developing second generation

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bioenergy crops (grasses and short rotation woody crops [SRWCs]), which further improve the GHG emission balance compared to first-generation corn ethanol.[13] These issues are reflected in biofuels policy frameworks such as the Renewable Energy Directive of the European Union[14] and the U.S. Energy Independence and Security Act (EISA) of 2007, which have a common mandate of increasing the relevance of dedicated energy crops in future biofuel portfolios. As a big part of the potential problems with large-scale bioenergy development depends on the ways it is deployed, alternative approaches to produce bioenergy feedstocks with minimal indirect land use change and impact on commodity production have been explored. These include allocation of marginal lands for lignocellulosic biomass production,[15–17] forest-residue-based biomass production,[18] utilization of corn stover and other agricultural residues,[19,20] and using cover crops[21] as well as algae.[22,23] The sustainable "by design" integration of perennial bioenergy crops into agricultural systems is a different emerging approach to increase overall productivity against limited land and water budgets, and with the potential for improving water quality and providing other environmental benefits.

THE UNDERLYING SCIENCE: ENVIRONMENTAL DEGRADATION, LANDSCAPE DESIGN, NUTRIENT RECOVERY, AND PHYTOREMEDIATION

Water quality degradation from agricultural activities can occur as the result of sedimentation due to soil erosion and accumulation of excess nutrients and pesticides via overland flow and leaching. Excessive soil erosion is both an economic and environmental problem since it removes the most fertile part of the soil profile leaving the land less productive. It can significantly impact stream-living organisms as the sediment and entrained pollutants disrupt the biotic and abiotic components of stream habitats.[24] Excessive amounts of nutrients, specifically nitrogen and/or phosphorus in surface waters can cause environmental health concerns such as hypoxia or low dissolved-oxygen condition in the water column, which is a major problem in some of the world's large water bodies like the Gulf of Mexico.[25] Hypoxic water conditions due to nutrient enrichment, massive algal bloom, and water column stratification can lead to fish kill and loss of benthic organisms.[26] Nutrient-contaminated surface and groundwater resources for potable water use also present a human health concern, particularly for infants,[27] and can make the cost of drinking water expensive due to high treatment requirements.

Sustainably integrating perennial bioenergy crops into agricultural lands relies on innovative approaches to land management and is in line with the current collective thrust of an integrative approach to food, feed, fiber, low-carbon energy production, while conserving water quality and maintaining the integrity of other ecosystem services.[28] This approach builds primarily on the physiological advantage of perennial bioenergy crops over row crops such as corn and soybean by proper placement and/or timing of production. Unlike corn and soybean, which require planting each growing season, perennial grasses, once established and properly managed will regrow each year on their own once minimum environmental conditions (particularly soil temperature above 10°C) exist, after their aboveground biomass is harvested. Perennial grasses are densely growing species and like SRWCs, have deeper rooting systems.[29] Hence, these crops are suitable for addressing water quality problems by minimizing soil erosion and recovering leached nutrients resulting from commodity crop production. To maximize benefits from perennial crops incorporated into agricultural landscapes for bioenergy, scientists propose the application of landscape design principles, in which perennial bioenergy crops can be strategically placed in areas within agricultural fields that are considered suboptimal for commodity crop production and/or exit points for excess chemicals (nutrients and pesticides) that have deleterious impacts to water quality.

Landscape design is an intentional change of the landscape patterns to meet multiple goals including cultural, socioeconomic, and sustainable ecosystem services.[30] In the context of commodity–bioenergy crop production and water quality benefits, landscape design involves the allocation of lands, often at the subfield scale,[31] to specific crops for maximum return spatially and temporally, and the targeted utilization of complementary crops with inherent characteristics that are beneficial for water quality protection. Perennial crops identified as suitable bioenergy feedstocks (e.g., switchgrass [*Panicum virgatum* L.], miscanthus [*Miscanthus giganteus*], big bluestem grass [*Andropogon gerardi*], prairie cordgrass [*Spartina pectinata*], willows [*Salix* spp.], poplars [*Populus* spp.], etc.) are well-suited to alleviate water quality issues due to their dense aboveground biomass growth, massive and deeper rooting systems, higher water and nutrient water use efficiencies, etc.,[29,32,33] which allow them to survive in areas

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where nutrient and water resources are scarce, or excessive. These characteristics make them suitable for removing excess nutrients leached in the subsurface soil or in the shallow groundwater system that cannot be accessed by shallower rooted annual commodity crops. Keeping the soil surface under vegetative cover is important for mitigating soil erosion. On a bare soil surface, soil erosion occurs as a two-step process: detachment of soil particles from the impact of raindrops and shearing effect of flowing water, particularly concentrated flow and subsequent transport of these particles by surface runoff or overland flow. Perennial grasses can be planted in areas that are vulnerable to erosion during the growing season and/or as double crops to provide cover for the soil after harvesting main crops. Grasses, due to their closely growing characteristics, can dissipate the energy of raindrops and minimize exposed soil surface areas, and have been used as vegetative filter strips to reduce concentrations of sediment and nutrient in overland flow[32,34,35] before it reaches surface waters. Additionally, they can take advantage of residual nutrients from main crop production that would otherwise become pollutants. Loss of nutrients from applied fertilizer is an economic loss and a source of GHGs. In addition to being expensive to produce, fertilizer represents a major cost of commodity crop production. For instance, fertilizer accounts for approximately 39% of direct cost of corn production in Illinois, USA.[36] Further, synthetic fertilizer production and use represent 75% of GHG emissions in corn production.[4] Thus, recovering these lost nutrients creates both economic and environmental benefits and parallels current trends in thinking about point source recovery from wastewater treatment plants.[37] Scaling up phytoremediation techniques from localized remediation to nonsource pollution control, SRWCs can be placed at locations within and around agricultural fields where large losses of labile nutrients like nitrate-N into the shallow groundwater occur, this time by percolation through the soil profile. Phytoremediation is a remediation method that uses plants to sequester, remove, or eliminate a given pollutant from soil and water systems.[38] Common SRWCs including willow and poplar have the ability to remediate entrained pollutants in shallow groundwater plume[39–41] and significantly reduce nutrient losses, particularly nitrate in the shallow groundwater systems.[42–45] In addition to improved water quality, integrating perennial grasses and SRWCs in agricultural landscapes has co-benefits, including potential for subsoil carbon sequestration[46] and habitat for pollinators[47] and other wildlife species.

INCORPORATION OF PERENNIAL BIOENERGY CROPS INTO AGRICULTURAL FIELDS FOR YIELDS AND WATER QUALITY BENEFITS

The techniques used in landscape design for producing perennial bioenergy feedstocks in agricultural fields while achieving water quality improvement[48,49] and other benefits with minimal indirect land use change impact[50–52] can be classified into three major categories: double cropping, mixed cropping, and intensified production (Figure 1). They can be used in both temperate and tropical agriculture to improve the sustainability of food, feed, and fiber production. While their use has mostly been driven by productivity goals, their use to improve water quality and diversify the landscape is an important co-benefit.

Double Cropping

Double cropping for bioenergy takes advantage of the temporal availability and suitability of lands for growing bioenergy crops following the harvest of commodity crops (Figure 1(a)). It is patterned on a soil and water conservation technique in temperate regions called cover cropping, where a second/cover crop is planted right after harvest of the main crop, to minimize soil surface exposure to rainfall and wind. This approach has dual advantages in addressing water quality issues. One, it provides cover for otherwise exposed bare soil and thereby minimizes soil erosion and two, it takes advantage of the excess nutrients in the soil from commodity crop production, which minimizes offsite losses of critical pollutants, particularly nitrate + nitrite nitrogen (nitrate). Double cropping is part of the proposed three efficient agricultural production approaches to produce enough biomass using 30% less of U.S. agricultural lands, yet produce biofuels that can displace 10% of the USA's annual GHG emissions.[53] Bioenergy double cropping trials in the United States and Europe have been primarily testing annual crops, including winter rye (*Secale cereale*),[54–56] winter triticale (*X Triticosecale Wittmack*),[57,58] winter camelina (*Camelina sativa* L.),[59,60] hairy vetch (*Vicia villosa*),[55] and turnip rape (*Brassica rapa* L.).[54] One study reported that relative to sole-corn cropping, a corn production double cropped with winter triticale for bioenergy could reduce potentially leachable soil N up to 34%.[55] Some of the perennial crops that could potentially be incorporated as double bioenergy crops to corn, soybean, and other main crops are perennial crops that could serve multiple uses including alfalfa (*Medicago sativa*) and perennial

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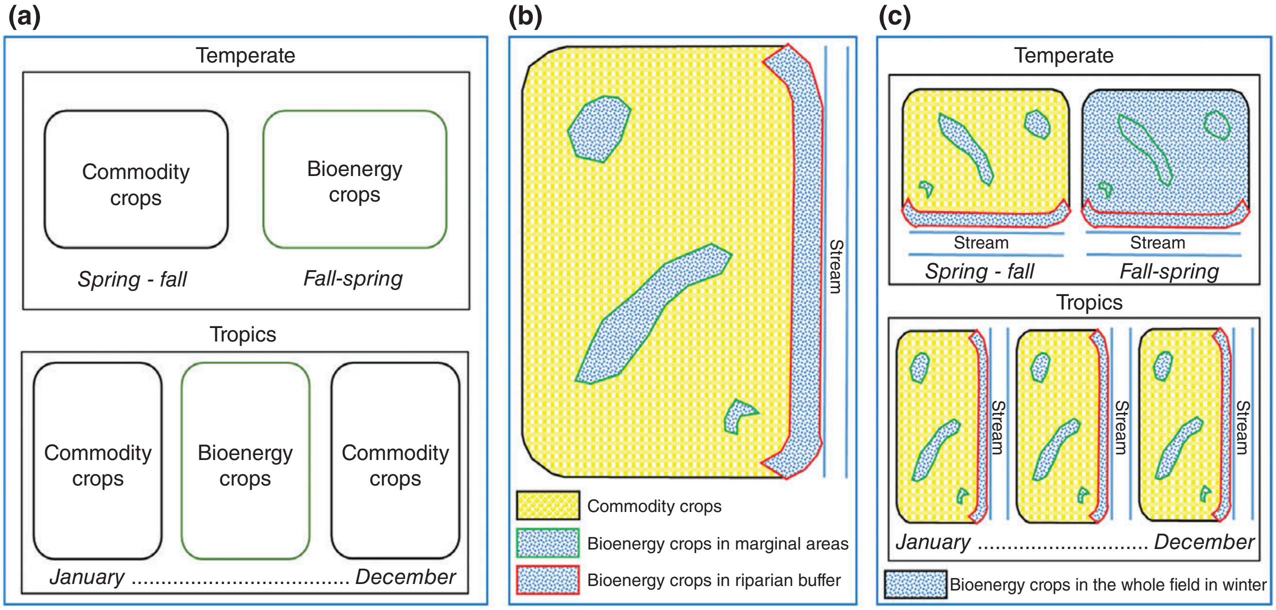

FIGURE 1 | Schematic of (a) double cropping scheme, (b) mixed cropping, and (c) intensive production across regions for biomass production and water quality improvement.

wheatgrass (*Thinopyrum intermedium*). For instance, protein feeds can be produced as co-products from alfalfa used for biofuel.[61] Similarly, grains of perennial wheatgrass can be made into flour, and serve as raw materials for brewery[62] and other applications,[63,64] while stems and grain husks can be used as biofuel feedstocks. In the tropics, potential bioenergy crops that have been proposed for double cropping are perennial leguminous plants including kudzu (*Pueraria phaseoloides*), which has been used as an alternative cover crop for maize-cassava production system in southwestern Nigeria[63] and pigeon pea (*Cajanus cajan*), which can serve as a double crop in a corn production system.[65]

Mixed Cropping

Mixed commodity and bioenergy cropping systems (Figures 1(b) and 2) take advantage of the spatial heterogeneity of the agricultural landscape in terms of resources for optimum crop growth. This approach lends itself to principles of landscape design: commodity crops will continue to be preferentially produced in most field areas that result in overall positive economic margins. Tools like the AgSolver's Profit Zone Manager (https://agsolver.com/) can be used to maximize profit under this system. Marginal areas on the same fields that are subfertile, or experiencing soil water stress (too dry or wet for commodity crops), and are exit points for water pollutants (e.g., riparian buffer, leachable soils) can be planted with perennial bioenergy crops. As previously discussed, perennial bioenergy crops may have higher water and nutrient use efficiency and a suite of other desirable traits.[33] If a biomass market is available, utilizing marginal agricultural soils for perennial bioenergy crops should prove profitable due to lower required production inputs and incentives derived from minimizing nutrient losses by placing these crops along riparian field edges.

An excellent example of mixed cropping platform to satisfy multifunctional objective, is the Strategic Trials of Row crops Integrated with Prairie Strips (STRIPS) Project in Iowa, USA (http://www.nrem.iastate.edu/research/STRIPs/). STRIPS project uses between 10 and 20% of the agricultural field for native perennials as filter strips within the field and contour buffer along riparian areas. Results of long-term studies showed that even by allocating only 10% of the field to strips, this approach can reduce up to 60% of overland flow,[66] 95% of sediment transport,[48] and 90% in P and total N losses,[49] respectively, relative to traditional row-crop production. These water quality benefits were attained without negative effects on adjacent row crops.[67] While STRIPS perennials are currently not harvested for bioenergy, it is estimated that they can provide an average biomass of 7.2 Mg ha^{-1} $year^{-1}$, which is comparable to switchgrass monoculture production in the region.[51] Similarly, SRWCs for bioenergy such as willow, can be strategically placed along contour buffers, particularly in areas with shallow

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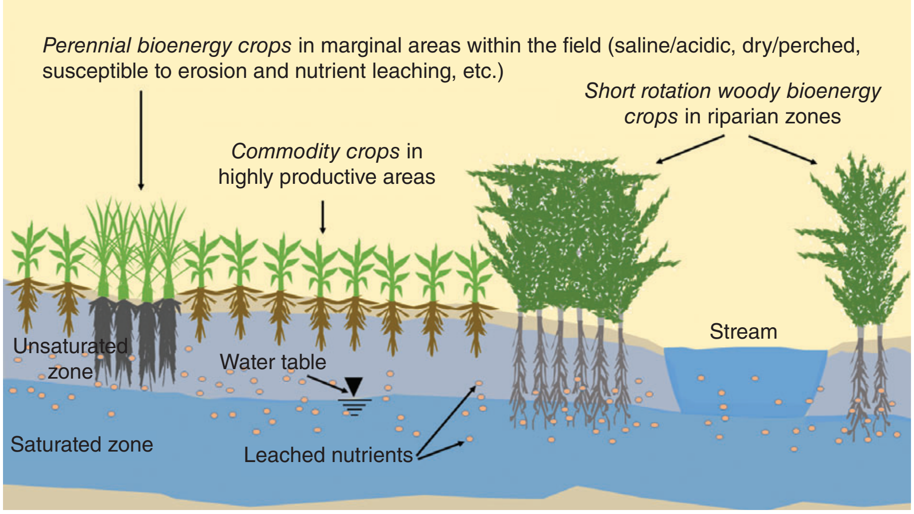

FIGURE 2 | Schematic of mixed cropping to optimize commodity and bioenergy crops production, while addressing water quality issues.

groundwater heavily loaded with mobile pollutants like nitrate. Results of a field study near Fairbury, IL showed that guided by soil characteristics, topography, and hydrology, willow for bioenergy can be carefully placed along sections of the contour areas of a continuous corn field and recover as much as 61% of nitrate lost from the field annually.[68] This system (placing a 0.32 ha saturated buffer on a 2.63 ha continuous corn field) can produce an average of up to 7.6 $\mathrm{Mg_{dry}\ ha^{-1}\ year^{-1}}$,[69] while displacing corn grain yield of 6.7 $\mathrm{Mg\ ha^{-1}\ year^{-1}}$.[68] If distributed landscape production of willow in a corn-dominated Midwestern U.S. agricultural watersheds is regarded as a nitrogen loss reduction practice, the net costs would be comparable to the commonly used best management practices[70] including controlled drainage, bioreactor, and constructed wetlands.[71] The use of perennial bioenergy buffers (miscanthus and willow) was also evaluated at a site in Po Valley, Italy along an agricultural field grown for corn, soybean, and tomato in rotation where on average, willow produced 17 $\mathrm{Mg\ DM\ ha^{-1}\ year^{-1}}$ and groundwater nitrate reduction of up to 80% depending on buffer width was observed.[72] Further, results of a study from multiple sites in Sweden showed that groundwater nitrate concentrations under a mature stand of commercially grown short rotation coppice willow were significantly lower than in adjacent agricultural fields, although the opposite was observed in the case of phosphate concentrations.[42]

Intensified Production

This approach (Figure 1(c)) is a combination of the two previous methods and theoretically can produce the highest bioenergy feedstock for a given field on an annual basis with similar or superior water quality benefits. It takes advantage of the temporal and spatial availability of land for bioenergy crop production without affecting commodity crop yields and is likely to have widespread adoption in the future as interests intensify in having an integrated food, feed, fiber, and energy production portfolio with maximum water quality benefits and other ecosystem services in agricultural landscapes.[51,53] In temperate areas, double cropping will likely be dominated by annual crops, including winter triticale, winter rye, and winter camelina, etc. as well as perennial crops such as alfalfa and winter wheatgrass since they can be used for biomass and other value-added applications[53,61,73] and farmers are already familiar with their production management needs. On the same fields, marginal areas and buffer zones will likely be grown with perennial grasses like switchgrass and miscanthus and SRWCs including willow and poplar to minimize input costs, recover excess nutrients from main and double crops, and minimize nutrient and sediment transport to receiving water bodies. In the tropics and semi-arid regions, crops like millet can serve as multipurpose (food, feed, and biomass) double crops. In Brazil, for instance, millet has shown potential as a companion double crop for upland rice production.[74] Leguminous plants like the *Mucuna pruriens var. utilis*, which can be used as cover crop/intercrop in corn production and has shown to have water quality and other benefits based on studies conducted in Benin, Cameroon, and Mexico[75,76] can be harvested as bioenergy feedstock. High yielding and deeply rooting perennial crops with relatively high water use and nutrient efficiencies including

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sugarcane (*Saccharum officinarum* L.) and napiergrass (*Pennisetum purpureum* Schumach.) can be grown on marginal areas and riparian zones of tropical agricultural landscapes together with high-yielding SRWCs like Eucalyptus.[77–79]

CHALLENGES AND OPPORTUNITIES

The main challenge to integrating perennial bioenergy crops in agricultural fields is the still uncertain market for cellulosic biofuels,[80,81] which impacts farmers' willingness and economic interest to adopt the system. Adoption of double cropping for bioenergy faces the same concerns as other double crops grown for different purpose. The primary technical concern is on its effects on the productivity of main crops. To avoid impacting water availability for the succeeding main crops and negative effects on their yield, careful balance needs to be achieved when planning double bioenergy crops grown on water-limited lands. In temperate regions, the desired soil base temperature for crop growth may not be attained early since the soil surface is covered with biomass and establishment of main crops could be delayed. Additionally, while perennial bioenergy crops may have soil carbon sequestration advantages and water quality benefits compared to annual counterparts, the cost of establishing these crops annually[21] may limit their adoption.

Marginal areas within agricultural fields are present in varying frequencies across different agricultural regions, with limited representation particularly in productive soils like the U.S. Midwest.[82] Hence, mixed cropping may not produce enough biomass quantity in every case to become economically enticing. At the more granular scale, marginal areas are also unevenly distributed in otherwise productive fields, and farm-level management related to establishment and harvesting operations could become logistically challenging, but potentially also economically favorable.[70] Even with increased biomass production using an intensified production approach, farmers may still be reluctant to adopt the system due to perceived economic disadvantage of biomass over commodity crops including insufficient markets, lower profits, and lack of widely available management practices to ensure successful crop production. Further, bioenergy crops are currently not covered by crop insurance,[83] another reason that could discourage farmer adoption of an integrated bioenergy–commodity crop production scheme.

Conversely, farmers' interest in integrating bioenergy crops in their production system could be increased due to the promise of better economic returns in marginal agricultural areas. Proper placement and allocation of bioenergy crops within and around agricultural fields to optimize biomass production and water quality benefits should no longer be a hindrance since a suite of technology platforms (e.g., geospatial technology, precision agriculture, etc.) is already available to do this and proven to work successfully with publicly available pertinent data. For instance in the United States, digital soil data from soil survey geographic (SSURGO) database,[84] geographic information systems (GIS), and remote and proximal sensing[85] can help identify areas within agricultural watersheds that are environmentally vulnerable and/or uneconomical for growing commodity crops and can then be planted with perennial bioenergy crops.[86] Similarly, on a field scale, a combination of the use of GIS and advanced surveying system, (e.g., Veris Mobile Sensor Platform [http://www.veristech.com/]), remote sensing[87] and AgSolver's Profit Zone Manager, and numerical modeling simulation can help identify critical bioenergy crop placement points for maximum water quality benefits with minimum impacts on main crops yield by providing information on the spatial variability of soils, variations in yields, surface and subsurface water flow directions, soil water nitrate concentrations, and main crop yield.[68] This approach could make techniques such as the STRIPS even more successful, through more surgical placement of variable perennial vegetative strip with widths based on the vulnerability of an area to water quality degradation. While traditional vegetative and buffer strips are usually fixed in width, STRIPS's vegetative filters are wider on areas that are identified to experience more overland flow.[66] Research is providing the knowledge basis for policy makers to develop effective and implementable policies. Providing farmers with economically viable practices could motivate them to employ perennial crops on environmentally vulnerable areas of their fields to satisfy soil and water conservation requirements of the crop insurance policy.[83] Increasing interest in the valuation of non-market ecosystem services which include, but are not limited to, water quality as a contributor to the overall economic value of a production system has also been proposed to support the sustainable integration of perennial bioenergy crops into commodity cropping systems and will be the focus of a future paper. Briefly, bioenergy crops are known to enhance soil health by maintaining macronutrient (N, P, K) contents[88] and enhancing soil organic carbon content[89–91] thereby minimizing fertilizer application requirement, associated cost, and potential nutrient

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losses. Integrating bioenergy crops into conventional commodity cropping has the potential to provide benefits to pollinating insects which prefer a more diverse landscapes.[92] This is important considering the ecosystem functions and economic values of wild insect pollinators,[93–96] and amid concerns of their declining populations[97] including butterflies,[90] hoverflies,[98] and bees[99] primarily due to agricultural intensification and land use change.[100,101]

CONCLUSION

Development of best practices is critical to encourage farmers to integrate perennial bioenergy crops into their commodity crop production system for water quality benefits and other ecosystem services. This could take some time since it requires more research efforts to solidify the science of this type of production scheme. In the meantime, lessons learned from past studies and eventually from ongoing research projects can enrich the current state of knowledge and allow for meta-analyses. Results of these analyses can be used to create manuals for farmers and other stakeholders to develop capabilities. Adopting a distributed processing system model[102,103] and availability of modeling tools such as the Biomass Logistics Model[104] for integrated analysis of bioenergy feedstocks supply system should help expand future markets since it paves the way for creating more outlets to biomass produced from small and large farms alike. Future markets for biomass, particularly in the United States, look promising as community-based biomass companies looking to boost local economy are starting to appear including the Madelia Model in Southern Minnesota (http://ruraladvantage.org/programs/the-madelia-model/), EcoSun Prairie Farms near Brookings, South Dakota (http://www.ecosunprairiefarms.org/), and Koda Energy in Shakopee, MN (http://www.kodaenergy.com/about-us/overview). Research in temperate regions, particularly in the European Union and the United States where most of the sustainable bioenergy studies are currently conducted, should be more focused on experiments at a watershed scale and in different agricultural landscapes (artificially drained versus undrained, different crop types, etc.) to determine if existing field results can be extrapolated to different systems at larger scales. More research efforts are needed in the tropics at the field and watershed scales to evaluate water quality and other benefits of commodity-perennial bioenergy crop integration for food, feed, fiber, and bioenergy production. This will be instrumental in developing best management practices that maximize the socioeconomic and environmental benefits, particularly water quality of this production system across regions, enrich the current state of knowledge, and allow for meta-analyses.

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