Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION INTERNATIONAL

OPINION ARTICLE

The Benefits of Harvesting Wetland Invaders for Cellulosic Biofuel: An Ecosystem Services Perspective

Andrew R. Jakubowski,[1,2] Michael D. Casler,[3] and Randall D. Jackson[1,4]

Abstract

The emerging interest in cellulosic biofuel production has led the call for alternative cropping systems that maximize production along with the accompanying regulating, supporting, and cultural ecosystem services. We evaluate the potential for biomass harvested from invaded wetlands to achieve these goals. The ecosystem service trade-offs associated with a wetland invader harvest are evaluated followed by a case study estimating the energy production and nutrient removal of harvesting *Phalaris arundinacea* from invaded wetlands in Wisconsin, United States. Estimates for energy production from this single species harvest dwarf current renewable energy sources for the state of Wisconsin and offer the potential to recapture approximately 50–200% of the excess nitrogen and phosphorus annually applied as fertilizer. This restoration technique would not only generate income from biomass sales to subsidize the cost of restoration, but also has the potential to shift the system toward more desirable environmental conditions by removing nutrients annually, reducing downstream eutrophication, and enhancing the ability of more desirable vegetation to establish by removing the litter layer created by the invasive species.

Key words: invasive species, novel ecosystems, nutrient management, *Phalaris arundinacea*, restoration.

Introduction

Although exotic invasive species continue to increase in abundance and reduce diversity, the demand for biomass as an energy feedstock is increasing (Pimentel et al. 2000; Hill et al. 2006; Field et al. 2008). Initial attempts to convert food production to biofuel production raised concerns over food shortages and increasing food prices (Pimentel & Patzek 2005). As a result of this concern, cellulosic biofuel production has shifted toward the use of abandoned or degraded agricultural lands that do not displace food production (Field et al. 2008; Tilman et al. 2009). Cropping marginal lands will require alternative crops and cropping systems to be successful on lands that are less productive, highly erodible, or difficult to manage (Robertson et al. 2008). However, there are alternatives to marginal, degraded, and currently cropped agricultural lands. Wetlands, although considered marginal for traditional agriculture, are ideal for the production of biomass, with wetlands dominated by invasive species of particular interest. Invaded wetlands produce a large amount of undesirable and unutilized biomass that can be harvested annually for cellulosic biofuel production. With the growing support for an expansion in restoration goals that work to explicitly restore ecosystem function and service in novel ecosystems, the combination of wetland restoration and cellulosic biofuel harvest of invaded wetlands is a promising method for restoring ecosystem services (Hobbs & Harris 2001; Suding et al. 2004; Seastedt et al. 2008).

Traditional restoration methods for invaded wetlands are improving, but long-term success rates remain low (Choi 2004). These low success rates are probably the result of biotic and abiotic influences of the surrounding uplands disrupting wetland ecosystems and shifting the system toward highly eutrophic, homogeneous, and disturbed conditions in which invasive species can thrive (Pimentel et al. 1995*a*; Hobbs et al. 2006). In wetlands that will continue to be disturbed because of the effects of the surrounding landscape, traditional historic community restoration will rarely be effective (Seastedt et al. 2008). However, emerging biomass markets for use as cellulosic biofuel creates an economic incentive to perform an ecosystem services-based restoration. This type of restoration would not only generate biomass for fuel, but would also work toward shifting a site toward more desirable environmental conditions by removing nutrients annually, reducing downstream eutrophication, and enhancing the ability of more desirable vegetation to establish by removing the litter layer created by the invasive species.

The objectives of this article are to (1) present the potential benefits of invasive plant biomass harvest to wetland restoration and (2) present a case study estimating the production and nutrient removal potential of a *Phalaris arundinacea* L. harvest in Wisconsin, United States.

[1] Department of Agronomy, University of Wisconsin-Madison, 1575 Linden Dr., Madison, WI 53706, U.S.A.
[2] Address correspondence to A. R. Jakubowski, email Jakubowski@wisc.edu
[3] USDA-ARS, U.S. Dairy Forage Research Center, 1925 Linden Dr., Madison, WI 53706, U.S.A.
[4] DOE-Great Lakes Bioenergy Research Center, University of Wisconsin-Madison, 1630 Linden Dr., Madison, WI 53706, U.S.A.

© 2010 Society for Ecological Restoration International
doi: 10.1111/j.1526-100X.2010.00738.x

Ecosystem Services-Based Restoration

Traditional restoration to remove undesirable species and restore historic diverse communities has limited value in highly altered environmental conditions (Hobbs et al. 2006). In sites where it is unfeasible to restore the biotic community, abiotic conditions, or both, a more constrained set of restoration goals that focus explicitly on improving ecosystem function may be more appropriate (Hobbs et al. 2009). An ecosystem services-focused restoration narrative is promising in wetlands where conditions have changed or where it is difficult or extremely expensive to alter the conditions in a wetland (i.e. a wetland surrounded by highly productive agricultural lands).

The potential benefits of harvesting wetland invaders from an ecosystem services perspective are many. All four general categories of ecosystem services can be addressed—provisioning, regulating, cultural, and supporting.

Provisioning. The most tangible ecosystem service is the provisioning service provided by the harvesting of the biomass for use as cellulosic biofuel. Invaded wetlands have no establishment cost for the producer, as all the vegetation is established. This provisioning service creates the economic incentive to enhance all other ecosystem services.

Regulating and Supporting. Wetlands and the vegetation that grow in them act as sponges or filters on the landscape for nutrients and water flowing from uplands (Zedler 2003). Nitrogen can be removed from the system through denitrification under anaerobic conditions (Sirivedhin & Gray 2006) or temporarily trapped via uptake by the plant community (Rogers et al. 1991). Phosphorus can be taken up by the plant community or physically trapped by vegetation within wetlands, but inputs can accumulate and be flushed from the system during senescence and flooding events (Jordan et al. 2003; Vymazal 2007). However, wetlands can become oversaturated and nutrients may begin to leak into downstream aquatic ecosystems (Osborne & Kovacic 1993). The nutrient removal and retention services of wetlands can be enhanced by an additional nutrient output from wetlands—biomass harvest. Harvesting the biomass from these areas can act as the wringing out of the sponge. Although the outputs of the system in the form of denitrification, removal of biomass, and other reverse nutrient pumps will not necessarily exceed the inputs into the system, any increase in nutrient outputs reduces eutrophication downstream. Any biomass harvest used for fuel also reduces carbon dioxide pollution, as this crop may be carbon neutral or negative (Adler et al. 2007).

Cultural. If a biomass harvesting system is maintained for a sufficient time (and ideally combined with improved management that reduces the disturbance caused by upstream systems), to the point where nutrient outputs exceed inputs, the environmental conditions may resemble those of historic conditions and will be more conducive to maintaining diverse and functional wetlands (Suding et al. 2004). These diverse wetlands may even be more productive than the current invasive monoculture, further contributing to the desire to continue the wetland harvest that is necessary to restore function and services to the wetland (Tilman et al. 2006).

Case Study: Reed Canarygrass in Wisconsin

There are several species of wetland invaders that are ideal for biomass harvest, with the specific species dependent on the location of the study. Potentially useful invaders in the central and eastern United States are *Phalaris arundinacea* (reed canarygrass), *Lythrum salicaria* (purple loosestrife), *Phragmites australis* (common reed), and *Typha* spp (cattail), as all are capable of forming dense monocultures.

In this study, we use reed canarygrass as our model for two reasons. The first is that the Wisconsin Department of Natural Resources has mapped reed canarygrass wetland invasion using remote sensing imagery. In Wisconsin alone, reed canarygrass has invaded more than 200,000 ha of wetlands (Hatch & Bernthal 2008). This acreage exceeds the amount that is currently enrolled in the Conservation Reserve Program in Wisconsin (201,635 and 186,353 ha, respectively; United States Department of Agriculture and Farm Service Agency 2009). Second, sufficient production and quality information exists in the ecological and agronomic literature to allow the development of reasonably accurate predictions for biomass production and conversion of reed canarygrass biomass to energy.

Methods

Estimates of potential biomass harvest, energy, and nutrient removal in Wisconsin were derived using estimates of the area of wetland invasion, the average production of aboveground biomass in an invaded wetland, and average energy and nutrient quality values of reed canarygrass biomass. Hatch and Bernthal (2008) developed an inventory of reed canarygrass invasion of Wisconsin using late-season Landsat imagery. Reed canarygrass is conducive to mapping using remote sensing imagery because of its late senescence in relation to other wetland species. The maps were created using the following process: the authors masked uplands in their analysis, developed a supervised classification of wetland invasion with two classifications (invaded having $>50\%$ cover of reed canarygrass in each 30-m^2 pixel and uninvaded having $<50\%$ cover) using mid-October images, and ground-truthed their classification at over 250 pixels to determine their accuracy. The overall accuracy of the classification exceeded 80%.

The aboveground production values used in the estimate were obtained by averaging values from six publications of wetlands in North America (Table 1). Only fall, single-cut harvest estimates were used for the estimate, although there are several possible harvest regimes determined by harvesting time and frequency such as a winter harvest or a harvest in spring and fall (Burvall 1997; Cherney et al. 2003). Aboveground biomass concentrations of nitrogen and

Table 1. Peak standing biomass values of *Phalaris arundinacea* growing in invaded wetlands and pastures in North America.

Reference	*Biomass (g/m^2)*	*Location*	*Habitat*
Lawrence and Ashford (1969)	1,134	Saskatchewan	Wet pasture
	681	Saskatchewan	Wet pasture
Klopatek and Stearns (1978)	1,353	Wisconsin	Marsh
Wedin and Helsel (1977)	1,370	New York	Wetland
Marten et al. (1979)	1,216	Minnesota	Treatment wetland
	1,242	Minnesota	Treatment wetland
Bernard and Lauve (1995)	1,408	New York	Treatment wetland
	1,713	New York	Treatment wetland
Jelinski et al. (2009)	937	Wisconsin	Invaded wet prairie
Mean	1,228		

Multiple values under a single reference indicate data collection at multiple sites or multiple years at the same site. All studies used a single-cut fall harvest regime.

Table 2. Nitrogen and phosphorus concentration values (as a percentage of dried biomass) of *Phalaris arundinacea.*

Reference	*Nitrogen Concentration (% DM)*	*Phosphorus Concentration (% DM)*	*Location*	*Habitat*
Cherney et al. (2003)	1.45	0.37	New York	Pasture
	1.55	0.29	New York	Pasture
	1.58	0.33	New York	Pasture
	1.78	0.35	New York	Pasture
	1.45	0.34	New York	Pasture
Kao et al. (2003)	1.57	0.19	New York	Wetland
McJannet et al. (1995)	1.20	0.23	Ottawa	Mesocosms
Mean	1.51	0.30		

Multiple values under a single reference indicate data collection for multiple years at the same site.

phosphorus were averaged from three publications (Table 2). Energy content values (J/g dry mass) were obtained from two publications (Burvall 1997; Paulrud & Nilsson 2001). The equations used for the energy and nutrient estimates were the following:

$$\text{Potential Energy (J)} = \text{Area (m}^2) \times \text{Production (g/m}^2) \times \text{Energy Coefficient (J/g)}$$

$$\text{Potential N Removal (g)} = \text{Area (m}^2) \times \text{Production (g/m}^2) \times \text{N Coefficient (g N/g biomass)}$$

$$\text{Potential P Removal (g)} = \text{Area (m}^2) \times \text{Production (g/m}^2) \times \text{P Coefficient (g P/g biomass)}$$

Estimates for Wisconsin used the estimate of the total area of reed canarygrass-invaded wetlands as the area parameter. Estimates at the 1:24,000-scale watershed and county scale were developed by defining the area parameter as the area of the invaded wetlands within the specified geographic unit. The estimates were developed using R 2.9.1 (R Development Core Team 2009). Energy-use statistics for Wisconsin were based on 2007 energy-use data in Wisconsin (Wisconsin Department of Energy Independence 2008). Estimates of fertilizer loss to aquatic systems were developed from Wisconsin Department of Agriculture, Trade, and Consumer Protection records of fertilizer purchase in Wisconsin in 2008 (Wisconsin Department of Agriculture Trade and Consumer Protection 2008) and low (10% nitrogen loss and 3% phosphorus loss) and high (40% nitrogen loss and 20% phosphorus loss) estimates for fertilizer loss to aquatic systems developed from Howarth et al. (1996) and Caraco (1995).

Results

The annual dry matter production estimate of the model for the state of Wisconsin was 2,406 Gg of biomass, and averaged 33.4 and 7.2 Gg per county and 1:24,000-scale watershed, respectively (Fig. 1). Energy production from this harvest would dwarf all renewable energy sources in Wisconsin, with the exception of the burning of wood, with the total potential harvestable energy equaling 43.1 petajoules (Fig. 2). This energy production would be sufficient to supply electricity for approximately 1.25 million Wisconsin households. Alternatively, as a heating fuel, the biomass could heat approximately 450,000 homes in Wisconsin, as approximately 0.45 ha of wetland would be needed to meet the heating needs of the average Wisconsin customer.

The nutrient removal accompanying this harvest was estimated to be 36.3 Gg of nitrogen removal and 7.2 Gg of phosphorus—approximately 191 and 225% of low estimates and

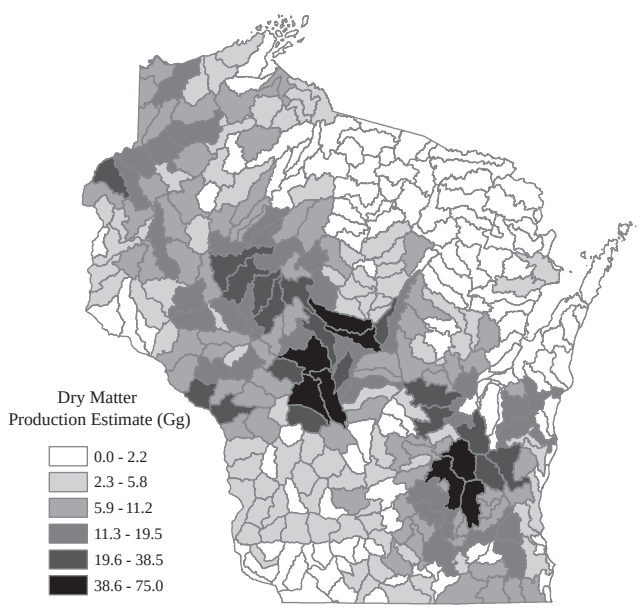

Figure 1. The annual production potential of reed canarygrass harvest in 1:24,000-scale watersheds in Wisconsin.

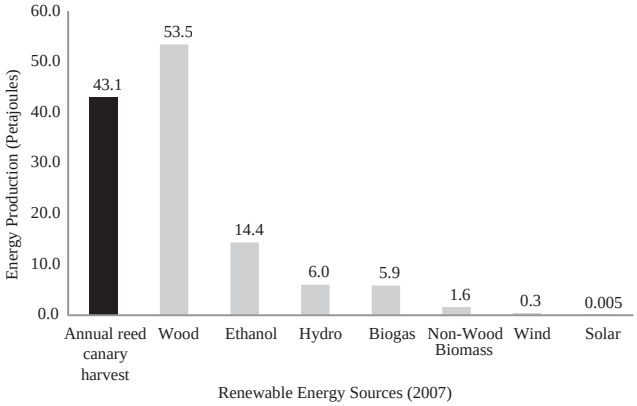

Figure 2. Current renewable energy sources used in Wisconsin (Wisconsin Office of Energy Independence 2008) contrasted against estimates of potentially available reed canarygrass harvest in Wisconsin.

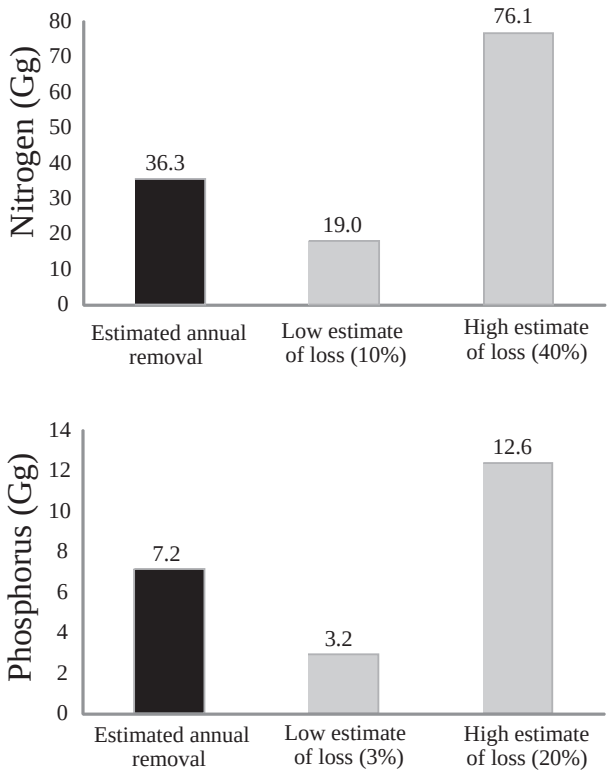

Figure 3. Potential nitrogen and phosphorus removal by reed canarygrass harvest in Wisconsin contrasted against estimates for fertilizer mineral component loss to aquatic systems. Estimates of fertilizer loss were developed from Wisconsin Department of Agriculture, Trade, and Consumer Protection records of fertilizer purchase in Wisconsin in 2008 and low (10% nitrogen loss and 3% phosphorus loss) and high (40% nitrogen loss and 20% phosphorus loss) estimates for fertilizer loss to aquatic systems from Howarth et al. (1996) and Caraco (1995).

48 and 57% of high estimates of fertilizer lost to aquatic systems in Wisconsin annually (Fig. 3). These nutrient removal values average 110 Mg of nitrogen and 20 Mg of phosphorus per watershed.

Discussion

History of Wetland Harvesting

The harvesting of wetlands for biomass is not a new idea. Marshes in North America have been harvested for hay since at least 1630, with the peak of harvesting occurring during the nineteenth century (Smith et al. 1989). The harvest of wetland biomass for use as energy dates back at least to the late 1970s when the U.S. Department of Energy established the National Renewable Energy Laboratory and the Aquatic Species Program (Sheehan et al. 1998). Historically, the focus of using wetlands for energy production has focused on establishing crops in wetlands to utilize these lands in agriculture. However, many ideal biofuel *crops* have invaded wetlands and are simply waiting for harvest. Pratt (1981) evaluated several wetland species and identified *Typha* × *glauca*, the hybrid cattail, as the ideal cropping system. The estimated annual aboveground production for this species was 1,806 g/m^2—47% greater average aboveground production than the reed canarygrass production parameter used in our analysis.

Difficulties and Logistics

Although it is not feasible to harvest 100% of invaded wetlands, even a 25–50% harvest would yield impressive energy and nutrient removal across the state. Our goal in this article is to provide a *what if* value for using invasive species as a biofuel, and we do not discount the difficulties associated with harvesting wetlands for biomass. Special equipment is necessary to harvest in wetlands and surrounding topology or bodies of water prohibit the access of harvesting equipment to many wetlands. In addition, many invaded wetlands still serve as important wildlife habitat and any harvesting program would need to balance trade-offs between these values. Given these issues, we are unable to provide an estimate for the percentage of wetlands that could be feasibly harvested. However, we believe that many wetlands can be harvested and the harvest could provide an immediate boost to cellulosic biofuel production systems while simultaneously enhancing the ecosystem services provided by invaded wetlands and providing an economic incentive to promote restoration.

Adaptive Restoration Goals

In addition to the physical and technical limitations to harvesting biomass from wetlands, there are other limitations to wetland harvest related to the goals of wetland restoration. Although traditional ecological community-based restoration is often an important and admirable goal, landscape- and ecosystem-level biotic and abiotic changes often make it unfeasible to achieve the restoration of historic communities (Hobbs et al. 2006; Seastedt et al. 2008). Yet, many restorations takes place at the site-specific scale, not because practitioners are oblivious to the effects of the surrounding landscape, but because the costs and political constraints are too great to restore the landscape in any way that could support and maintain the historic community (Lindenmayer et al.

2008). By using an ecosystem services framework to develop and evaluate goals for restoration, even disturbed sites set in a disturbed landscape can be managed to improve the services that they provide. Although one can argue that this activity does not constitute restoration in its strictest sense, our goal is to complement traditional restoration, not replace it. We believe this pragmatic restoration style offers the potential to enhance ecosystem function and services in highly altered or disturbed sites where traditional methods are unlikely to be successful.

We are not suggesting that all degraded wetlands be harvested or that a wetland that is presently degraded be harvested indefinitely. Rather, we are suggesting an adaptive restoration plan that continually evaluates the restoration and ecosystem service goals for a site and the restoration techniques to be used at that site based on the landscape context, community dynamics, ecosystem dynamics, and social goals for the site (Zedler 2000). This holistic approach allows restoration plans to define what goals are achievable for a site and objectively evaluate the trade-offs in ecosystem services provided by different types of restoration.

The Importance of Good Policy

Developing policy to regulate wetland harvest will be essential to achieve conservation goals and avoid wetland exploitation. It is not difficult to imagine a perverse scenario where landowners are intentionally fertilizing or introducing invasive species to uninvaded wetlands in an attempt to expand their harvest area or increase production. We offer two reasonable policy options to avoid this issue. The first is the development of a biomass sales permit that would be required of anyone interested in selling biomass for use as biofuel. This permit would outline rules for harvest and sale and could be combined with existing noxious weed laws that prohibit the sale and establishment of listed species. Violators of these guidelines would be subject to a fine or suspension of their biomass sale permit.

A more stringent policy would require producers to complete a certification process prior to being allowed to sell biomass. This certification process would require the producer to undergo a site evaluation, agree to follow best management practices and act in accordance with biomass harvesting rules, and develop a management plan that protects wildlife and works to reduce invasive species cover on their property. Again, violators would be subject to fines or suspension of their certification. Although this type of policy would allow for much greater control of what and how wetlands are harvested, the cost of the certification process and enforcement would be much greater than a simple permitting process.

Recapturing Nutrients Lost from Agriculture by Reversing the Pump

The current system of nutrient addition to the landscape via fertilization has overwhelmed the ability of wetlands to remove nutrients via denitrification, plant uptake, physical entrapment, or movement of consumers from wetlands to uplands (Pimentel et al. 1995*b*; Gende et al. 2004; Gibbons et al. 2006; Gratton et al. 2008; Quinn et al. 2009). To counteract this increase in fertilizer use, additional means of removing or redistributing nutrients from lowlands to uplands are necessary. The harvesting of wetland biomass has the potential to recapture some of the nutrients lost to overland flow and to help prevent these nutrients from flowing downstream. Much of the nitrogen in the biomass will be volatilized through combustion, although some nitrogen will be released to the atmosphere (Lobert et al. 1990). Nonvolatile nutrients such as phosphorus, potassium, magnesium, and sodium are recovered in the ash following combustion of the biomass (Obernberger et al. 1997). This ash can be collected and utilized as a fertilizer (Prochnow et al. 2009), helping to enhance the nutrient link between uplands and lowlands and increase the nutrient use efficiency of agriculture (Tilman et al. 2002).

Assessing the Potential for Biomass Harvest to Enhance Ecosystem Diversity

An annual biomass harvest of wetlands offers the potential to restore diversity to invaded wetlands for several reasons. The first is the annual removal of nutrients from the wetland system. This harvest utilizes the ability of the undesirable plant species to mine the soil for nutrients and translocate them into aboveground tissue (Nichols 1983). Repeated harvests combined with improved nutrient management upstream offer the potential for nutrient outputs to exceed inputs in a wetland. Over time, biomass harvest may create a more nutrient-limited environment where diverse ecosystems are more likely to thrive (Tilman 1987, 1996; Huenneke et al. 1990). In addition, biomass harvest can eliminate the litter layer from a wetland that limits light availability to the seed bank and suppresses the establishment of native species (Gordon 1998). Biomass removal reduces the advantage previously established vegetation has over seedling establishment (Callaway & Walker 1997). Biomass harvest may serve as a form of passive restoration of the ecological community that works to alter the environmental conditions that facilitated the establishment and persistence of undesirable species in place of the desirable community.

Incentivizing Restoration to Provide Multiple Ecosystem Services

Although the ecosystem services framework is useful to ecologists in identifying the benefits of restoration, scientists and policy makers continue to struggle to assess and fund projects designed to improve ecosystem services (Carpenter et al. 2009). Yet, provisioning ecosystem services (biomass production) already have a commodity price associated with them. Therefore, when a provisioning service is accompanied by the enhancement of other ecosystem services, there is economic incentive to enhance regulating, supporting, and cultural ecosystem services. This incentive exists without the

need for any subsidies. Thus, biomass harvest has the potential to be an economic driver for restoration activity, while capturing the nutrients flowing downstream from agricultural fields to reduce the eutrophication of wetlands and water bodies downstream of the harvested wetland.

Conclusion

The harvesting of invaded wetlands for use as cellulosic biofuel provides a means to enhance the ecosystem services provided by highly disturbed wetlands. Although there are technical limitations to harvesting in wetlands, there are few establishment and opportunity costs associated with wetland harvest. The biomass harvested from these lands is ideal for cellulosic biofuel production, as the biomass production does not displace food production or rely on marginal lands for production. We estimate the production of reed canarygrass, but there are several species of wetland invaders ideal for harvest. This harvest has the potential to provide an enormous boost to both the cellulosic biofuel and restoration industries by providing a large supply of biomass that is immediately available for harvest and sale. The potential amount of renewable energy from this harvest would more than double the current sources of renewable energy in Wisconsin (when excluding wood burning). The nutrients that accompany the biomass harvest help to recapture nutrients lost to erosion from uplands and reduce eutrophication downstream. If the harvest of a wetland is continued over a sufficiently long period and nutrient outputs exceed nutrient inputs, the wetland may be able to shift to environmental conditions that favor a diverse, desirable, and functional plant community and ecosystem. We suggest that the technical and economic feasibility of degraded wetland harvest for cellulosic biofuel be explored further, as the ecological process could greatly enhance the ecosystem services provided by degraded wetlands.

Implications for Practice

- Emerging biomass markets for use as cellulosic biofuels will create an opportunity for land managers to utilize the sale of harvested invasive species biomass as an economic driver for restoration.
- In highly altered sites, biomass harvest is another tool for land managers to reduce invasive species cover, reduce eutrophication, and enhance diversity.
- Effective policy will be essential to assure that the harvesting of wetland biomass will be used to achieve restoration goals, not to meet an increasing demand for invasive biomass.

Acknowledgments

This work was funded in part by GLCI grant 941-3 and by the DOE-Great Lakes Bioenergy Research Center (DOE Office of Science BER DE-FC02-07ER64494).

LITERATURE CITED

Adler, P. R., S. J. Del Grosso, and W. J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications **17:**675–691.

Bernard, J. M., and T. E. Lauve. 1995. A comparison of growth and nutrient uptake in *Phalaris arundinacea* L. growing in a wetland and a constructed bed receiving landfill leachate. Wetlands **15:**176–182.

Burvall, J. 1997. Influence of harvest time and soil type on fuel quality in reed canary grass (*Phalaris arundinacea* L.). Biomass and Bioenergy **12:**149–154.

Callaway, R. M., and L. R. Walker. 1997. Competition and facilitation: a synthetic approach to interactions in plant communities. Ecology **78:**1958–1965.

Caraco, N. F. 1995. Influence of human populations on P transfers to aquatic systems: a regional scale study using large rivers Pages 235–244 in H. Tiessen, editor. Phosphorus in the global environment. John Wiley & Sons, New York.

Carpenter, S. R., H. A. Mooney, J. Agard, D. Capistrano, R. S. Defries, S. Diaz, et al. 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. Proceedings of the National Academy of Sciences of the United States of America **106:**1305–1312.

Cherney, J. H., D. J. R. Cherney, and M. D. Casler. 2003. Low Intensity Harvest Management of Reed Canarygrass. Agronomy Journal **95:**627–634.

Choi, Y. D. 2004. Theories for ecological restoration in changing environment: toward 'futuristic' restoration. Ecological Research **19:**75–81.

Field, C. B., J. E. Campbell, and D. B. Lobell. 2008. Biomass energy: the scale of the potential resource. Trends in Ecology & Evolution **23:**65–72.

Gende, S. M., T. P. Quinn, M. F. Willson, R. Heintz, and T. M. Scott. 2004. Magnitude and fate of salmon-derived nutrients and energy in a coastal stream ecosystem. Journal of Freshwater Ecology **19:**149–160.

Gibbons, J. W., C. T. Winne, D. E. Scott, J. D. Willson, X. Glaudas, K. M. Andrews, et al. 2006. Remarkable amphibian biomass and abundance in an isolated wetland: implications for wetland conservation. Conservation Biology **20:**1457–1465.

Gordon, D. R. 1998. Effects of invasive, non-indigenous plant species on ecosystem processes: lessons from Florida. Ecological Applications **8:**975–989.

Gratton, C., J. Donaldson, and M. Zanden. 2008. Ecosystem linkages between lakes and the surrounding terrestrial landscape in Northeast Iceland. Ecosystems **11:**764–774.

Hatch, B. K., and T. W. Bernthal. 2008. Mapping Wisconsin wetlands dominated by reed canary grass, *Phalaris arundinacea* L.: a landscape level assessment. PUB-WT-900-2008. Wisconsin Department of Natural Resources, Madison, Wisconsin.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States of America **103:**11206–11210.

Hobbs, R. J., and J. A. Harris. 2001. Restoration ecology: repairing the Earth's ecosystems in the new millennium. Restoration Ecology **9:**239–246.

Hobbs, R. J., S. Arico, J. Aronson, J. S. Baron, P. Bridgewater, V. A. Cramer, P. R. Epstein, J. J. Ewel, C. A. Klink, and A. E. Lugo. 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecology & Biogeography **15:**1–7.

Hobbs, R. J., E. Higgs, and J. A. Harris. 2009. Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution **24:**599–605.

Howarth, R. W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J. A. Downing, R. Elmgren, N. Caraco, and T. Jordan. 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry **35:**75–139.

Huenneke, L. F., S. P. Hamburg, R. Koide, H. A. Mooney, and P. M. Vitousek. 1990. Effects of soil resources on plant invasion and community structure in Californian serpentine grassland. Ecology **71:**478–491.

Jelinski, N. A., C. J. Kucharik, and J. B. Zedler. 2009. A test of diversity & productivity models in natural, degraded, and restored wet prairies. Restoration Ecology. DOI: 10.1111/j.1526-100X.2009.00551.x.

Jordan, T. E., D. F. Whigham, K. H. Hofmockel, and M. A. Pittek. 2003. Nutrient and sediment removal by a restored wetland receiving agricultural runoff. Journal of Environmental Quality **32:**1534–1547.

Kao, J. T., J. E. Titus, and W. X. Zhu. 2003. Differential nitrogen and phosphorus retention by five wetland plant species. Wetlands **23:**979–987.

Klopatek, J. M., and F. W. Stearns. 1978. Primary productivity of emergent macrophytes in a Wisconsin freshwater marsh ecosystem. American Midland Naturalist **100:**320–332.

Lawrence, T., and R. Ashford. 1969. Effect of stage and height of cutting on the dry matter yield and persistence of intermediate wheatgrass, bromegrass, and reed canarygrass. Canadian Journal of Plant Science **49**:321–332.

Lindenmayer, D., R. J. Hobbs, R. Montague-Drake, J. Alexandra, A. Bennett, M. Burgman, P. Cale, A. Calhoun, V. Cramer, and P. Cullen. 2008. A checklist for ecological management of landscapes for conservation. Ecology Letters **11:**78–91.

Lobert, J. M., D. H. Scharffe, W. M. Hao, and P. J. Crutzen. 1990. Importance of biomass burning in the atmospheric budgets of nitrogen-containing gases. Nature **346:**552–554.

Marten, G. C., C. E. Clapp, and W. E. Larson. 1979. Effects of municipal wastewater effluent and cutting management on persistence and yield of eight perennial forages. Agronomy Journal **71:**650–658.

McJannet, C. L., P. A. Keddy, and F. R. Pick. 1995. Nitrogen and phosphorus tissue concentrations in 41 wetland plants: a comparison across habitats and functional groups. Functional Ecology **9:**231–238.

Nichols, D. S. 1983. Capacity of natural wetlands to remove nutrients from wastewater. Journal of the Water Pollution Control Federation **55:**495–505.

Obernberger, I., F. Biedermann, W. Widmann, and R. Riedl. 1997. Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. Biomass and Bioenergy **12:**211–224.

Osborne, L. L., and D. A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology **29:**243–258.

Paulrud, S., and C. Nilsson. 2001. Briquetting and combustion of spring-harvested reed canary-grass: effect of fuel composition. Biomass and Bioenergy **20:**25–35.

Pimentel, D., and T. W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural Resources Research **14:**65–76.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. Mcnair, et al. 1995*a*. Environmental and economic costs of soil erosion and conservation benefits. Science **267:**1117–1123.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. Mcnair, S. Crist, L. Shpritz, L. Fitton, and R. Saffouri. 1995*b*. Environmental and economic costs of soil erosion and conservation benefits. Science **267:**1117–1123.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. Bioscience **50:**53–65.

Pratt, D. C. 1981. Wetland biomass production Pages 119–126. Proceedings of the July 1981, Subcontractors' Review Meeting Aquatic Species Program. Solar Energy Research Institute, Golden, Colorado.

Prochnow, A., M. Heiermann, M. Plöchl, T. Amon, and P. J. Hobbs. 2009. Bioenergy from permanent grassland—a review: 2. Combustion. Bioresource Technology **100:**4945–4954.

Quinn, T. P., S. M. Carlson, S. M. Gende, and H. B. Rich Jr. 2009. Transportation of Pacific salmon carcasses from streams to riparian forests by bears. Canadian Journal of Zoology **87:**195–203.

R Development Core Team. 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Robertson, G. P., V. H. Dale, O. C. Doering, S. P. Hamburg, J. M. Melillo, M. M. Wander, et al. 2008. Sustainable Biofuels Redux. Science **322:**49–50.

Rogers, K. H., P. F. Breen, and A. J. Chick. 1991. Nitrogen removal in experimental wetland treatment systems: evidence for the role of aquatic plants. Research Journal of the Water Pollution Control Federation **63:**934–941.

Seastedt, T. R., R. J. Hobbs, and K. N. Suding. 2008. Management of novel ecosystems: are novel approaches required? Frontiers in Ecology and the Environment **6:**547–553.

Sheehan, J., T. Dunahay, J. Benemann, and P. Roessler. 1998. A look back at the US Department of Energy's Aquatic Species Program—biodiesel from algae. Report No. NREL/TP-580-24190, National Renewable Energy Laboratory, Golden, Colorado.

Sirivedhin, T., and K. A. Gray. 2006. Factors affecting denitrification rates in experimental wetlands: field and laboratory studies. Ecological Engineering **26:**167–181.

Smith, D. C., V. Konrad, H. Koulouris, E. Hawes, and H. W. Borns Jr. 1989. Salt marshes as a factor in the agriculture of Northeastern North America. Agricultural History **63:**270–294.

Suding, K. N., K. L. Gross, and G. R. Houseman. 2004. Alternative states and positive feedbacks in restoration ecology. Trends in Ecology & Evolution **19:**46–53.

Tilman, D. 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. Ecological Monographs **57:**189–214.

Tilman, D. 1996. Biodiversity: population versus ecosystem stability. Ecology **77:**350–363.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature **418:**671–677.

Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science **314:**1598–1600.

Tilman, D., R. Socolow, J. A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, and C. Somerville. 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science **325:**270–271.

United States Department of Agriculture and Farm Service Agency. 2009. Conservation Reserve Program Monthly Summary—June 2009. 1-CRP (Revision 1).

Vymazal, J. 2007. Removal of nutrients in various types of constructed wetlands. Science of The Total Environment **380:**48–65.

Wedin, W. F., and Z. R. Helsel. 1977. Plant species for biomass production on marginal Sites Pages 34–48 in M. R. Institute, editor. Conference on Production from grasses, crop residues, forage legumes, and grasses for conversion to fuels and chemicals. Midwest Research Institute, Kansas City, Missouri.

Wisconsin Department of Agriculture Trade and Consumer Protection. 2008. 2007–2008 fertilizer summary (available from http://www.datcp.state.wi.us/arm/agriculture/pest-fert/fertilizers/pdf/2008FertSummary.pdf) accessed 14 December 2009.

Wisconsin Office of Energy Independence. 2008. Wisconsin energy statistics (available from http://energyindependence.wi.gov/subcategory.asp?linksubcatid=2825&linkcatid=2847&linkid=1451&locid=160) accessed 20 November 2009.

Zedler, J. B. 2000. Progress in wetland restoration ecology. Trends in Ecology & Evolution **15:**402–407.

Zedler, J. B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. Frontiers in Ecology and the Environment **1:**65–72.