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Life cycle assessment of nutrient remediation and bioenergy production potential from the harvest of hydrilla (*Hydrilla verticillata*)

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A B S T R A C T

Hydrilla (*Hydrilla verticillata*) is one of the world's most problematic invasive aquatic plants. Although management of hydrilla overgrowth has often been based on use of chemical herbicides, issues such as the emergence of herbicide-resistant hydrilla biotypes and the need for *in situ* nutrient remediation strategies have together raised interest in the use of harvester machines as an alternative management approach. Using a life cycle assessment (LCA) approach, we calculated a range of net energy and economic benefits associated with hydrilla harvests and the utilization of biomass for biogas and compost production. Base case scenarios that used moderate data assumptions showed net energy benefit ratios (NEBRs) of 1.54 for biogas production and 1.32 for compost production pathways. NEBRs for these respective pathways rose to 2.11 and 2.68 when labor was excluded as a fossil fuel input. Base case biogas and compost production scenarios respectively showed a monetary benefit cost ratio (BCR) of 1.79 and 1.83. Moreover, very high NEBRs (3.94 for biogas; 6.37 for compost) and BCRs (>11 for both biogas and compost) were found for optimistic scenarios in which waterways were assumed to have high hydrilla biomass density, high nutrient content in biomass, and high priority for nutrient remediation. Energy and economic returns were largely decoupled, with biogas and fertilizer providing the bulk of output energy, while nutrient remediation and herbicide avoidance dominated the economic output calculations. Based on these results, we conclude that hydrilla harvest is likely a suitable and cost-effective management program for many nutrient-impaired waters. Additional research is needed to determine how hydrilla harvesting programs may be most effectively implemented in conjunction with fish and wildlife enhancement objectives.

1. Introduction

Controlling the overgrowth of invasive exotic aquatic plants is a primary concern for managers of freshwater ecosystems throughout the world. Over the past several decades hydrilla (*Hydrilla verticillata*) has emerged as the most costly invasive aquatic plant in the southeast U.S., where tens of millions of dollars are annually spent on efforts to combat the species (Schmitz, 2007). Likely native to southern Asia, hydrilla is a submersed aquatic plant originally imported into the U.S. by the aquarium trade (Langeland, 1996). By the late 1950s, careless disposal of excess aquarium plants led to the establishment of self-sustaining hydrilla populations in several Florida ecosystems. Since that time hydrilla has rapidly spread by means of boat trailers and propellers into many lakes, rivers, and reservoirs throughout the U.S. southeast. In addition, a separate strain of more cold-tolerant hydrilla has more recently become established throughout the northern U.S. (Steward et al., 1984; Les et al., 1997). Throughout its introduced range, hydrilla has become notorious for forming dense mats of "topped-out" vegetation that can displace native plants, impede navigation, clog flood control devices, and reduce aesthetic enjoyment of affected aquatic systems (Center et al., 1995; Langeland, 1996).

Most large-scale attempts at managing hydrilla overgrowth have historically been based upon use of chemical herbicides. However, several issues raise questions about the long-term sustainability of this management approach. First, researchers have found several distinct hydrilla biotypes with an evolved resistance to fluridone, the most commonly used and cost-efficient herbicide for hydrilla control, in a number of Florida lakes (Michel et al.,

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2004). While significant effort and resources are being devoted to development of new herbicide formulations (Puri et al., 2009), the apparent plasticity and adaptability of hydrilla makes it plausible, perhaps even probable, that similar resistance against alternative compounds will be developed over time (Richardson, 2008). Second, large-scale senescence of aquatic plants from herbicidal control has the undesirable effect of rapidly liberating large amounts of phosphorus (P), nitrogen (N), and other contaminants of concern into the water column (e.g., Hodgson and Carter, 1982; Gu, 2006). Such nutrient releases can turn trigger major algal blooms in treated water bodies (Bates and Hentges, 1976; Hodgson and Carter, 1982), and potentially in downstream systems that receive the pulsed nutrient fluxes. Given growing concerns with harmful algal blooms (e.g., Heisler et al., 2008) and the ongoing implementation of nutrient mitigation programs for many watersheds (e.g., Haire et al., 2007), there is a clear impetus for development of hydrilla control techniques that are more sensitive to the issue of nutrient liberation (Gu, 2006). Finally, some ecological research indicates that moderate levels of hydrilla coverage can have high habitat value for many native fish and wildlife species (Schramm and Jirka, 1989; Esler, 1990; Bonvechio and Bonvechio, 2006). One long-term research study in the Chesapeake watershed found that habitat benefits from hydrilla may be especially pronounced for ecosystems that are in a “recovery” phase following removal of nutrient burdens associated with cultural eutrophication (Rybicki and Landwehr, 2007). Due to such observed habitat effects, important user groups such as sports anglers and bird watchers have in recent years openly advocated for increased hydrilla coverage and opposed large-scale chemical control options in some ecosystems (Jones and Beardall, 2009; Hoyer et al., 2008).

Taken together, these issues have recently led some researchers and managers to suggest that alternatives to chemical treatment should be more widely considered, particularly in those systems where hydrilla coverage is already widespread and eradication is not feasible (Bonvechio and Bonvechio, 2006; Gu, 2006; Jones and Beardall, 2009; Hoyer et al., 2008). One of the primary alternatives for managing overgrowth of hydrilla and other aquatic plants is use of harvester machines to remove excess biomass from the water body. Although a wide body of scientific literature has long noted the nutrient mitigation benefits (e.g., Carpenter and Adams, 1978; McGehee, 1979; Mericas et al., 1990; Mahujchariyawong and Ikeda, 2001) and potential utilization options (e.g., Bates and Hentges, 1976; Abbasi et al., 1990; Hronich et al., 2008) associated with harvest of aquatic plant biomass, mechanical harvest of hydrilla has often been regarded by aquatic managers as inefficient and cost-prohibitive when compared to chemical control (e.g., Langeland, 1996; Hoyer et al., 2005).

However, there is good reason to believe that such assumptions about the cost-prohibitiveness of hydrilla harvest may not be valid for many systems. Most specifically, the recent emergence of herbicide-resistance has had the effect of rapidly escalating the monetary and non-target costs associated with chemical control of resistant hydrilla biotypes (Richardson, 2008). More broadly, the control efficiency argument often is predicated on the presumption that successful management of hydrilla is solely a function of minimizing plant populations, rather than as one system component that should be evaluated in concert with other major ecosystem objectives such as nutrient mitigation and wildlife habitat. When considered in these contexts, it is reasonable to at least suspect that large-scale mechanical harvesting of hydrilla may be an appropriate and beneficial management alternative for some freshwater ecosystems.

To develop a more thorough understanding of these issues, we used a life cycle approach to quantify major energy, material, and monetary flows associated with mechanical harvest of hydrilla and the subsequent use of harvested biomass for bioenergy and organic fertilizer production. While several past studies have either examined ecosystem effects of mechanical harvesting (McGehee, 1979; Haller et al., 1980; Mericas et al., 1990) or potential bioenergy production yields from hydrilla (Abbasi et al., 1990), this study is to our knowledge the first that integrates these variables into one comprehensive analysis. As such, results from this study should be directly relevant for managers of freshwater ecosystems affected by hydrilla or other invasive aquatic plants, as well as for sustainability researchers and policy-makers engaged with the emerging bioenergy economy.

2. Methods and materials

2.1. Life cycle assessment

In the most general terms, a life cycle assessment (LCA) is a material accounting and decision-support tool that systematically quantifies the necessary inputs, beneficial outputs, and, in some cases, the negative externalities associated with a given process or product (Pehnt, 2006). The rationale for the LCA method is that it provides a straightforward, quantitative basis for comparing important costs and benefits for one process to those of alternative or competing processes. Although most LCAs have explicitly focused on the material flows of environmental variables such as fossil energy usage, greenhouse gas emissions, and eutrophication potential (e.g., Kim and Dale, 2005; Hill et al., 2006; Huijbregts et al., 2006; Pehnt, 2006; von Blottnitz and Curran, 2007), the LCA method is also increasingly being used as a means of creating more systems-based monetary cost analyses (e.g., Reich, 2005; Rabl and Holland, 2008).

A primary metric of interest for bioenergy LCAs is the net energy balance ratio (NEBR). The NEBR is defined as the sum of bioenergy produced and fossil fuel energy expenditures avoided through the process, divided by the sum of fossil fuel energy consumed by the process (see, e.g., Hill et al., 2006; Evans and Cohen, 2009). Energy equivalents are calculated through the use of coefficients that describe the amount of embodied fossil energy used in the input process, or the amount of fossil energy that would be required to produce an equivalent output through an alternative manufacturing process. NEBR results over 1 indicate a corresponding net yield from the process, while values less than 1 indicate that the process is an energy sink that requires more energy inputs than outputs.

Monetary equivalents for inputs and outputs can also be derived using a similar process as that described for net energy calculations. A primary metric of interest in the monetary balance is the benefit cost ratio (BCR), which is the sum of monetary equivalents for products and avoided costs divided by monetary investments for inputs. Similarly to the NEBR, a BCR over 1 indicates correspondingly higher benefits than costs, whereas a BCR of less than 1 indicates that monetary costs are greater than benefits.

2.1.1. Process description

The standard procedure for developing an LCA is to define the analytic boundaries of the process being analyzed, list all the inputs, outputs, and externalities of interest, and then define a convenient “functional unit” over which all of these variables will be quantified. Although the functional unit is crucial for consistent calculations within a study, the choice of a functional unit ultimately is arbitrary. For example, functional units for recently published LCAs of liquid biofuels have been disparately defined in different studies as 1 l of biofuel (Hill et al., 2006), 1000 l of biofuel (Pimentel and Patzek, 2005), and 1 ha of biofuel feedstock production (Evans and Cohen, 2009).

In this study, the process of interest was defined as mechanical harvest of hydrilla from a lake with an established hydrilla population and no feasible method for permanent eradication of the plant. In addition, two utilization options were considered for harvested hydrilla biomass: 1) supplemental feedstock source for biogas and organic fertilizer production in a regional anaerobic digestion facility; and 2) a soil amendment produced at a lakeside composting facility. The functional unit of the LCA was defined as 1 ha of aquatic plant harvesting. The goal of the LCA was to calculate a range of NEBRs and BCRs for each process, thereby providing guidance into the conditions in which hydrilla harvest might be an appropriate management strategy, and also determining which output factors are most important for achieving net energy and monetary returns.

2.1.2. Input parameters

The hydrilla harvest process requires three input categories: steel machinery (aquatic plant harvester and backhoe), diesel fuel, and human labor. Data for hydrilla harvesting were obtained through communications with the principals of Moss Monster, Inc., a company that has harvested hydrilla at several lakes in central Texas for the past decade. Embodied fossil energy values obtained from recent bioenergy LCAs (Pimentel and Patzek, 2005; Hill et al., 2006; Hronich et al., 2008) were used as the coefficients for each of these input categories. The additional input categories of biomass handling and transportation were included to account for aggregated machinery and fossil fuel demands associated with the handling and transport of hydrilla biomass to an off-site biogas facility. Energy and dollar costs for handling wet hydrilla biomass were assumed as similar to water hyacinth, an invasive aquatic plant that was recently studied by Hronich et al. (2008) for potential use as an ethanol feedstock. Embodied fossil energy and dollar costs for transportation of dry biomass to a biogas facility were calculated based upon an assumed distance of 40 km. Handling and transport costs were neglected for compost production at a lakeside composting facility, based on the assumption that handling and transport would not differ significantly from those associated with current disposal practices that are already internalized into the life cycle of the harvest operation. All data, energy coefficients, cost estimates, and corresponding references for input parameters are summarized in Supplementary Tables 1–3.

2.1.3. Output parameters

The basic output of the harvesting process is wet biomass of hydrilla. Embedded within this wet biomass are the following five variables of interest from a life cycle perspective: 1) dry biomass; 2) area harvested; 3) nitrogen mass; 4) phosphorus mass; and 5) potassium mass. The embodied energy return for hydrilla dry biomass, which is approximately 10% of wet biomass, was calculated as the biogas energy yield from anaerobic digestion of the plant. Economic return for this biogas was calculated as the market value for an equivalent energy of natural gas. The energy and economic returns for harvest area were calculated in terms of avoided use of fluridone, the most commonly used herbicide for hydrilla control. Nitrogen, phosphorus, and potassium mass were all calculated as a respective percentage of dry biomass. Energy credit for displacing fossil fuels in fertilizer production and monetary credit for fertilizer value were given in relation to the nitrogen, phosphorus, and potassium content of hydrilla biomass. Additional fossil energy and monetary credits were calculated based upon the inputs required for removal of nitrogen and phosphorus through other nutrient remediation methods. All data, energy coefficients, cost estimates, and corresponding references for output parameters are summarized in Supplementary Tables 1–3.

2.1.4. Multiple iterations

As with all LCAs, the results of this study are wholly dependent upon the accuracy and applicability of data used. Because there are considerable uncertainties and variability inherent to the process of harvesting and utilizing hydrilla, it is thus desirable to perform multiple iterations for the purpose of representing a range of plausible values. For this study, we began with a “base case” scenario that was carefully constructed as a best attempt at matching real world conditions. Two additional scenarios were then performed: one based on data assumptions that are highly optimistic for the hydrilla harvest process, and another based on highly pessimistic assumptions. The optimistic scenario describes a situation in which hydrilla can be harvested at the most efficient level, and also where maximum energy and monetary credit offsets are provided. A real world analogue to this scenario would be a highly eutrophic lake with a highly developed watershed that has little room for implementation of the lowest cost nutrient mitigation strategies. By contrast, the pessimistic scenario describes a situation of low harvesting efficiency and minimal energy and monetary credits. The real world analogue for the pessimistic case is a low productivity lake that does not allow for optimal harvest of hydrilla, and that has a watershed with sufficient undeveloped land area for low cost nutrient mitigation strategies. Because inclusion of labor as a fossil fuel equivalent input has been questioned by some LCA researchers (e.g., Kim and Dale, 2005; Farrell et al., 2006), we performed calculations for all scenarios with labor both included and excluded as an energy input.

3. Results

The energy inputs and outputs for each hydrilla harvest and utilization scenario are presented in Table 1. Energy returns from analyses with labor inputs included range from a 59% loss in the pessimistic composting scenario, to an over three-fold energy return in the optimistic composting scenario. Monetary returns are considerably more variable, with the pessimistic case showing a loss of 83% for the biogas production pathway, while the optimistic case shows over an eleven-fold economic return for the biogas and composting pathways. As summarized in Fig. 1, the relative energy and monetary values associated with product exports (i.e., biogas and fertilizer) and lake management benefits (i.e., nutrient remediation and herbicide avoidance) are quite decoupled for the hydrilla harvest process.

Net energy benefit ratio (NEBR) and benefit cost ratio (BCR) for the base case both are greater than 1, which indicates that there are net energy and monetary returns associated with the process using moderate data assumptions. In general, the NEBRs from the base case are comparable to those for corn ethanol production in the U.S., which have been recently calculated as between 1.25 (Hill et al., 2006) and 1.62 (Kim and Dale, 2005). Because harvesting of aquatic plants is a very labor-intensive process, exclusion of labor as a fossil fuel input changes the results considerably. Notably, the NEBR is over 2 for both of the base case scenarios, and the NEBR of 3.94 for the optimistic biogas scenario is comparable to the NEBR of 3.67 for soybean biodiesel reported by Hill et al. (2006). When labor was excluded from the pessimistic scenarios, a modestly positive NEBR was calculated for biogas production, while a modest loss of 13% was shown for the composting pathway.

4. Discussion

A key point that emerges from these results is that dedicated biogas and fertilizer production from harvested hydrilla, while attractive from a renewable energy production perspective, is not favorable from a life cycle economic perspective. Indeed, it is

Table 1
Energy and monetary LCA balances for hydrilla harvest and utilization.

	Base (MJ)	Optimistic (MJ)	Pessimistic (MJ)	Base ($)	Optimistic ($)	Pessimistic ($)
Inputs						
Machinery	31	31	31	1189.50	1189.50	1189.50
Fuel	750	750	750	15.00	15.00	15.00
Labor	800	800	800	150.00	150.00	150.00
Handling	660	990	300	22.00	33.00	11.00
Transport	682	413	341	8.80	13.20	4.40
Total (biogas)	2933	2984	2252	1385.30	1400.70	1369.90
Total (compost)[a]	1581	1581	1581	1354.50	1354.50	1354.50
Outputs						
Biogas	2420	3630	990	2.20	6.60	1.10
Avoided herbicide	157	473	80	242.00	730.40	173.60
N Remediation	46	392	9	1531.20	4312.00	55.80
N Fertilizer	1479	2856	459	7.83	15.10	2.43
P Remediation	31	326	1	686.40	10472.00	3.42
P Fertilizer	27	286	2	0.55	5.71	0.05
K Fertilizer	350	644	91	14.00	25.80	3.64
Total (biogas)	4510	8607	1632	2484.18	15567.61	189.64
Total (compost)[b]	2090	4977	642	2481.98	15561.01	188.54
Biogas benefit ratio[c]	**1.54 (2.11)**	**2.88 (3.94)**	**0.72 (1.12)**	**1.79**	**11.11**	**0.14**
Compost benefit ratio[b, c]	**1.32 (2.68)**	**3.14 (6.37)**	**0.41 (0.82)**	**1.83**	**11.49**	**0.14**

[a] Biomass handling and transport costs are not included for compost pathway.

[b] Biogas is not included as an output for compost pathway.

[c] Benefit ratio is defined as net energy benefit ratio (NEBR) for energy (MJ) columns, and benefit to cost ratio (BCR) for dollar columns. NEBR values in parentheses are calculated without inclusion of labor hours as a fossil fuel input.

notable that the combined economic value of biogas and organic fertilizer is not sufficient to cover handling and transportation costs in any of the scenarios, much less the significantly higher cost of harvesting (e.g., >$2400/ha; Hoyer et al., 2005) as compared to chemical control of fluridone susceptible populations (~$880/ha; Richardson, 2008). These economic results help to explain the observation by Gajalakshmi et al. (2006) that, despite several decades of research into biogas production from aquatic weeds, this utilization process has been rarely adopted at anything beyond small pilot scale experiments.

However, another key point is that aquatic plant harvesting can be a very cost-effective component of nutrient remediation for lake systems (Reisinger et al., 2008). Moreover, a plausible argument can be made that existing and environmental costs currently borne for waste disposal should be diverted into production of a renewable energy resource, particularly in cases where hydrilla or other

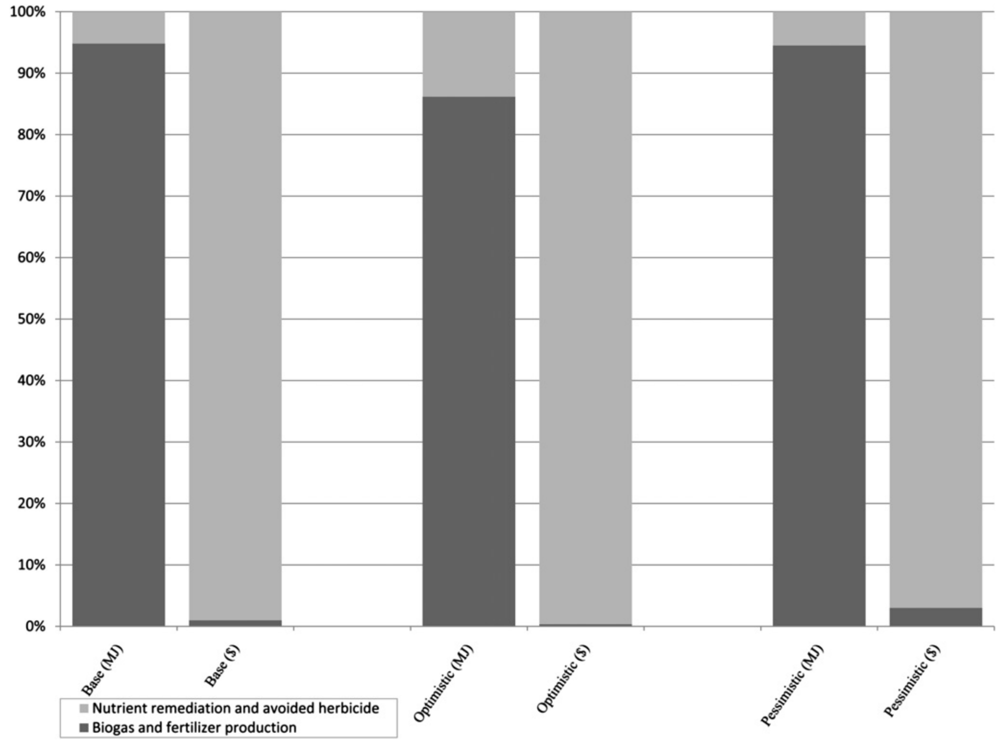

Fig. 1. Comparison of the relative energy (MJ) and monetary ($) contributions from material exports (i.e., biogas and fertilizer production) and in-lake benefits (i.e., nutrient remediation and avoided herbicide) associated with hydrilla harvesting scenarios.

aquatic weeds are currently being harvested and transported for disposal at an off-site landfill. Productive use of the harvested hydrilla biomass in such cases, whether for biogas or compost, would also have the supplementary beneficial effect of avoiding fugitive methane emissions associated with aquatic plant overgrowth (Banik et al., 1993; Cronin et al., 2006), anoxic conditions that develop in the aftermath of in-lake senescence of plants after herbicide treatment (Strange, 1976), or landfill disposal of harvested plant biomass (Themelis and Ulloa, 2007). While not accounted for in this analysis, mitigation of methane emissions is environmentally beneficial because atmospheric methane has several times the solar radiative efficiency and, thus, global warming potential of carbon dioxide (Boucher et al., 2009).

Although the data and inputs for this analysis were largely gathered from the southeast U.S., the methods and results of this study should be applicable to other regions in which hydrilla overgrowth is a serious ecosystem management concern. For example, it can be generally expected that the biomass density and nutrient content of hydrilla will be highest in those lakes with significant nutrient remediation concerns. In such systems, the benefits of hydrilla harvest may well approach those suggested by the optimistic case results. The benefits of harvesting are likely even more pronounced in lakes with fluridone-resistant hydrilla populations, as the management costs associated with higher levels of fluridone loading and/or use of alternative herbicides may be several times higher than those assumed in any of our scenarios (e.g., Hoyer et al., 2005). At the same time, the pessimistic case indicates that lower fertility lakes with relatively sparse hydrilla coverage would be poor candidates for harvester management, as life cycle monetary costs for this method would be several times higher than the benefits. It should also be noted that if hydrilla coverage is local and/or sporadic through a given lake, harvesting could have the additional counterproductive effect of spreading viable plant fragments into new areas (Langeland, 1996).

Other factors not formally analyzed in this paper, such as wildlife and fishery habitat, obviously are also quite important when considering hydrilla harvest as a management tool. Although there is a growing consensus that moderate coverage (20–40%) of hydrilla provides excellent habitat for most fish and wildlife (Bonvechio and Bonvechio, 2006), past studies about the direct effects of aquatic plant harvesting on fish populations have found disparate results. On the one hand, Haller et al. (1980) found significant by-catch removal of valuable sports fish during hydrilla harvests in Orange Lake, FL. Based on these results Haller et al. (1980) argued that whole-lake hydrilla harvests had the potential to significantly reduce fish populations, particularly in the context of small lakes. On the other hand, two studies of Wisconsin lakes found that aquatic plant harvests were associated with beneficial growth rate increases and age-class diversity in largemouth bass, likely as a result of increased structural habitat diversity provided by harvest activities (Engel, 1987; Unmuth and Hansen, 1999). Similarly, Mericas et al. (1990) argued that a systematic approach of maintaining alternate rows of harvested and un-harvested hydrilla would be beneficial for sports fish habitat in Lake Okeechobee, FL. Because available research studies are sparse and do not provide any general guidance into expected fishery effects from hydrilla harvest, lake-specific field observations and monitoring of fish populations are clearly warranted for lakes in which large-scale harvesting is implemented as a primary management strategy.

5. Conclusions

This study provides a comprehensive LCA of energy and economic balances associated with harvest of hydrilla and utilization of biomass for biogas and compost production. Net energy and economic gains were found using moderate data assumptions, which suggests that plant harvest may be an attractive management strategy for many lakes affected by hydrilla. However, the respective energy and economic value outputs are largely decoupled, as energy output is dominated by biogas and fertilizer output, while economic output is dominated by the value of removing nutrients from aquatic systems and avoiding the use of herbicides. Thus, use of harvested material as a supplementary feedstock for renewable energy and/or compost production, while attractive in their own right from a sustainability perspective, likely are predicated on lake management decisions that more fully account for the economic linkages between aquatic plant control, nutrient remediation, and habitat enhancement.

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References

Abbasi, S.A., Nipaney, P.C., Schaumber, G.D., 1990. Bioenergy potential of eight common aquatic weeds. Biol. Wastes 34, 359–366.

Bates, R.P., Hentges, J.F., 1976. Aquatic weeds: eradicate or cultivate? Econ. Bot. 30, 39–50.

Banik, A., Sen, M., Sen, S.P., 1993. Methane emissions from waterhyacinth-infested freshwater ecosystems. Chemosphere 27, 1539–1552.

Bonvechio, K.I., Bonvechio, T.F., 2006. Relationship between habitat and sport fish populations over a 20-year period at west Lake Tohopekaliga, Florida. N. Am. J. Fish. Manage. 26, 124–133.

Boucher, O., Friedlingstein, P., Collins, B., Shine, K.P., 2009. The indirect global warming potential and global temperature change potential due to methane oxidation. Environ. Res. Lett. 4. doi:10.1088/1748-9326/4/4/044007.

Carpenter, S.R., Adams, M.S., 1978. Macrophyte control by harvesting and herbicides: implications for phosphorus cycling in Lake Wingra, Wisconsin. J. Aquat. Plant Manage. 16, 20–23.

Center, T.D., Frank, J.H., Dray, F.A., 1995. Biological invasions: stemming the tide in Florida. Florida Entomol. 78, 45–55.

Cronin, G., Lewis, W.M., Schiehser, M.A., 2006. Influence of freshwater macrophytes on the littoral ecosystem structure and function of a young Colorado reservoir. Aquat. Bot. 85, 37–43.

Engel, S., 1987. The impact of submerged macrophytes on largemouth bass and bluegills. Lake Reservoir Manage. 3, 227–234.

Esler, D., 1990. Avian community response to hydrilla invasion. Wilson Bull. 102, 427–440.

Evans, J.M., Cohen, M.J., 2009. Regional water resource implications of bioethanol production in the southeastern United States. Global Change Biol. 15, 2261–2273.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammean, D.M., 2006. Ethanol can contribute to energy and environmental goals. Science 311, 506–508.

Gajalakshmi, S., Abbasi, T., Abbasi, S.A., 2006. Energy from anaerobic digestion of phytomass: an enduring but unrealized dream. Indian Chem. Eng. Section B 48, 109–111.

Gu, B., 2006. Environmental conditions and phosphorus removal Florida lakes and wetlands inhabited by *Hydrilla verticillata* (Royle): implication for invasive species management. Biol. Invas. 8, 1569–1578.

Haire, M.S., Schoen, M.E., Shoemaker, L., Vega, R., 2007. The development of watershed scale TMDLs. In: Proceedings of the Water Environment Federation. TMDL, pp. 250–260.

Haller, W.T., Shireman, J.V., DuRant, D.F., 1980. Fish harvest resulting from mechanical control of hydrilla. Trans. Am. Fish. Soc. 109, 517–520.

Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H.G., Sellner, K., Stockwell, D.A., Stoecker, D.K., Suddleson, M., 2008. Eutrophication and harmful algal blooms: a scientific consensus. Harmful Algae 8, 3–13.

Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS 103, 11206–11210.

Hodgson, L.M., Carter, C.C., 1982. Effect of hydrilla management by herbicides on a periphyton community. J. Aquat. Plant Manage. 20, 17–19.

Hoyer, M.V., Netherland, M.D., Allen, M.S., Canfield, D.E., 2005. Hydrilla Management in Florida: A Summary and Discussion of Issues Identified by Professionals with Future Management Recommendations. Dept. of Fisheries and Aquatic Sciences, University of Florida, Gainesville. http://myfwc.com/docs/WildlifeHabitats/InvasivePlants_HydMgtChlngs06.pdf (accessed December 2009).

Hoyer, M.V., Woods Jackson, M., Allen, M.S., Canfield, D.E., 2008. Lack of exotic hydrilla infestation effects on plant, fish and aquatic bird community measures. Lake and Reservoir Manage. 24, 331–338.

Hronich, J.E., Martin, L., Plawsky, J., Bungay, H.R., 2008. Potential of *Eichhornia crassipes* for biomass refining. J. Ind. Microbiol. Biotechnol. 35, 393–402.

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., Meent, D.V.C., Ragas, A.M.J., Reijnders, L., Struijs, J., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40, 641–648.

Jones, R.M., Beardall, H., 2005. Florida hydrilla management summit: facilitator's summary report. December 6–7, Orlando, Florida. Conflict Resolution Consortium. www.floridadep.net/lands/invaspec/2ndlevpgs/pdfs/SummitReportEdit10-06.pdf (accessed December 2009).

Kim, S., Dale, B.E., 2005. Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. Biomass Bioenergy 28, 475–489.

Langeland, K.A., 1996. *Hydrilla verticillata* (L.F.) Royle (Hydrocharitaceae), "The perfect aquatic weed". Castanea 61, 293–304.

Les, D.H., Mehrhoff, L.J., Cleland, M.A., Gabel, J.D., 1997. *Hydrilla verticillata* (Hydrocharitaceae) in Connecticut. J. Aquat. Plant Manage. 35, 10–14.

Mahujchariyawong, J., Ikeda, S., 2001. Modelling of environmental phytoremediation in eutrophic river – the case of water hyacinth harvest in Tha-chin River, Thailand. Ecological Model. 142, 121–134.

McGehee, J.T., 1979. Mechanical hydrilla control in Orange Lake, Florida. J. Aquat. Plant Manage. 17, 58–61.

Mericas, D., Gremillion, Pl, Terczak, E., 1990. Aquatic weed removal as a nutrient export mechanism in Lake Okeechobee, Florida. In: Berger, J.J. (Ed.), Environmental Restoration: Science and Strategies For Restoring the Earth. Island Press, Washington, pp. 203–211.

Michel, A., Arias, R.S., Scheffler, B.E., Duke, S.O., Netherland, M., Dayan, F.E., 2004. Somatic mutation-mediated evolution of herbicide resistance in the nonindigenous invasive plant hydrilla (*Hydrilla verticillata*). Mol. Ecol. 13, 3229–3237.

Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy 31, 55–71.

Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; Biodiesel using soybean and sunflower. Nat. Resour. Res. 14, 65–76.

Puri, A., Haller, W.T., Netherland, M.D., 2009. Cross-resistance in fluridone-resistanct hydrilla to other bleaching herbicides. Weed Sci. 57, 482–488.

Rabl, A., Holland, M., 2008. Environmental assessment framework for policy applications: life cycle assessment, external costs and multi-criteria analysis. J. Environ. Planning Manage. 51, 81–105.

Reich, M.C., 2005. Economic assessment of municipal waste management systems – case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). J. Cleaner Prod. 13, 253–263.

Reisinger, D.L., Brabham, M., Schmidt, M.F., Victor, P.R., Schwartz, L., 2008. Methodology, evaluation, & feasibility study of total phosphorus removal management measures in Lake George and nearby lakes. Florida Water Resour. J., 42–50.

Richardson, R.R., 2008. Aquatic plant management and the impact of emerging herbicide resistance issues. Weed Technol. 22, 8–15.

Rybicki, N.B., Landwehr, J.M., 2007. Long-term changes in abundance and diversity of macrophyte and waterfowl population in an estuary with exotic macrophytes and increasing water quality. Limnol. Oceanogr. 52, 1195–1207.

Schmitz, D.C., 2007. Florida's invasive plant research: historical perspective and the present research program. Nat. Areas J. 27, 251–253.

Schramm, H.L., Jirka, K.J., 1989. Effects of aquatic macrophytes on benthic invertebrates in two Florida lakes. J. Freshwater Ecol. 5, 1–12.

Steward, K.K., Van, T.K., Carter, V., Pieterse, A.H., 1984. Hydrilla invades Washington, D.C. and the Potomac. Amer. J. Bot. 71, 162–163.

Strange, R.J., 1976. Nutrient release and community metabolism following application of herbicide to macrophytes in microcosms. J. Appl. Ecol. 13, 889–897.

Themelis, N.J., Ulloa, P.A., 2007. Methane generation in landfills. Renewable Energy 32, 1243–1257.

Unmuth, J.M.L., Hansen, M.J., 1999. Effects of mechanical hervesting of Eurasian watermilfoil on largemouth bass and bluegill populations in Fish Lake, Wisconsin. N. Am. J. Fish. Manage. 19, 1089–1098.

von Blottnitz, H., Curran, M.A., 2007. A review of assessments conducted on bioethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J. Cleaner Prod. 15, 607–619.