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Undergraduate Research Articles

Life cycle analysis for the cultivation and combustion of miscanthus for biofuel compared with natural gas

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ABSTRACT

As negative environmental and economic impacts of fossil fuels have escalated, so has the importance of renewable bioenergy crops whose feedstocks are noncompetitive with food supplies. Compared with fossil fuels, use of lignocellulosic feedstocks offers potential for greenhouse gas reduction and highly positive net energy returns because of low input demand and high yields per unit of land area, thus making them advantageous for the emerging biofuel industry. The aim of this study was to simulate environmental impacts of producing a biofuel grass for combustion use based on the inventory of inputs and their effects on eutrophication of surface waters; acidification of land and water; photochemical ozone-creation potential (i.e. smog); global atmospheric warming; and nonrenewable resource depletion (mainly fossil fuels). Hybrid miscanthus (*Miscanthus* x *giganteus*, or giant miscanthus), a perennial C4 grass originating from East Asia, was compared with natural gas by using a life-cycle analysis model for biomass production in France. The analysis showed a trade-off between natural gas and miscanthus. The latter had a lower global-warming potential and consumed less primary nonrenewable energy but produced more emissions that promote acidification and eutrophication than did natural gas.

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MEET THE STUDENT-AUTHOR

Amanda Ashworth

I am from Fayetteville, Ark., and a graduate of Fayetteville High School. At present, I am a graduating senior at the University of Arkansas majoring in Environmental, Soil, and Water Science with minors in Spanish and Global Agriculture, Food, and Life Sciences. I am a member of the Crop, Soil, and Environmental Sciences Club.

During my career at the University of Arkansas, I spent a year studying at the Universidad de Granada to complete my Spanish minor. I also received two Americorp Education Awards through my completion of two Student Conservation Association (SCA) internships. One internship included conserving native-plant populations in Montana with the USDA Forest Service, and the second internship was with the Bureau of Land Management in California working on safeguarding dry-land species against extinction. Since last May, I have worked in the Crop, Soil, and Environmental Sciences Department as a lab and greenhouse assistant on native-plant propagation for wetland/riparian restoration and biomass production.

The research project reported in this paper was made possible by the Renewable Resources and Clean Technology International Program, and through partnership of the National Polytechnic Institute of Toulouse, France, and the University of Arkansas. A poster presentation of this study was presented at the International Conference on Renewable Resources and Biorefineries in The Netherlands in June 2008.

I would like to give special thanks to Drs. Charles West and Michael Popp of the University of Arkansas for their advice on this project. Sincere appreciation is extended to Caroline Sablayrolles and Mireille Montrejaud-Vignoles for hosting my spring semester at the Ecole Nationale Supérieure des Ingénieurs en Arts Chimiques et Technologiques (ENSIACET), and for the expert knowledge and guidance they devoted to this project.

I started my master's degree program in the Crop, Soil, and Environmental Sciences Department in August 2008, with Dr. West as my advisor. My graduate research plans include continuing this study using bioethanol as the endpoint, and researching switchgrass biomass and nutrient accumulation in Arkansas.

INTRODUCTION

Life-cycle analysis (LCA) is a cradle-to-grave environmental diagnostic tool that calculates energy and material inputs and outputs of potential pollutants at every stage of fuel production and consumption. Such analyses are critical for comparing alternatives to fossil fuels to maximize energy efficiency and minimize environmental degradation. Replacing fossil fuels with plant-derived feedstocks causes a decrease in net carbon emissions because of withdrawal of carbon from the atmosphere during photosynthesis, thereby theoretically reducing net greenhouse gas (GHG) emissions. Little is known, however, about the magnitude of potentially negative environmental impacts and trade-offs in harnessing the sun's energy through combusting plant biomass. Life-cycle analyses are also useful to determine the most efficient practices for biomass production, transport, storage, and processing in terms of being least cost and least detrimental to the environment (Schmer et al., 2008), and thus have relevance for policy making and industrial-scale design of bioenergy systems.

This LCA aims to quantify the nature and magnitude of pollution trade-offs when analyzing the perennial grass, hybrid miscanthus (*Miscanthus* x *giganteus*, or giant miscanthus), as an alternative to natural gas. Miscanthus is classified as lignocellulosic biomass feedstock because the entire plant is used. Most of the gross energy is contained in the fibrous (lignin, cellulose, and hemicellulose) component of the plant. Such a feedstock can be used directly for heat and electrical power generation through simple combustion, which aids in reducing greenhouse gas emissions through direct replacement of fossil fuels. In comparison, production of corn (*Zea mays* L.) for bioethanol is currently the main source for ethanol production in the U.S.; however, corn provides minimal net benefits in terms of reducing fossil energy consumption and GHG emissions (Tillman et al., 2006).

Miscanthus was chosen for this study because it produces high biomass yields with low levels of industrial inputs, such as fertilizer, pesticides, and irrigation (Clifton-Brown et al., 2004), when compared with annual crops like corn. In contrast, annual crop production destabilizes soil through repeated cycles of soil cultivation, crop establishment, and harvest, which lead to higher erosion than perennial crops (Lewandowski and Schmidt, 2006). Perennial crops such as miscanthus have the added advantage of not requiring annual tillage and planting operations, which further reduces energy inputs and negative environmental impacts. We hypothesized that miscanthus production for use in heat and power generation results in a lower release of GHG and ozone-creating compounds that induce smog, but a greater release of compounds inducing eutrophication and acidification when compared with fossil fuels such as natural gas.

MATERIALS AND METHODS

Four phases of this analysis included 1) goal and scope definition, 2) life cycle inventory, 3) life cycle inventory assessment, and 4) interpretation of data. Figure 1 illustrates the production and collection stages for the two fuels in this comparison. The analysis included all the agricultural processes involved in producing biomass and subsequent direct combustion, such as stand establishment, application of fertilizers, machinery for transportation and harvest, and pesticides as well as estimating GHG emitted during these processes. A range of environmental parameters were analyzed and aggregated into the following impact categories: resource depletion (comprising primary, mainly fossil, energy consumption to supply electricity and buildings, machinery, chemicals, etc.); acidification; eutrophication; creation of photochemical ozone (smog) via nitrous oxide emission (e.g. depletion of the protective stratospheric ozone); and greenhouse gas emissions for calculating global warming potential (GWP) with a time horizon of 500 years (Table 1). Global warming potential is an indicator of the heat retention capacity of a gas to impact climate. This LCA does not include any economic or social functions, nor does it calculate net energy yield or net energy ratio of biofuel production systems. Renewable energies that contribute to the primary energy pool and other indirect energies that contribute to crop production, such as human labor, are considered as outside the system.

We used the LCA methods and input/output outlined by Institut für Energie und Umweltforschung (IFEU) (Institute of Energy and Environmental Research Heidelberg, 2000) and the pollution standards of the Association Française de Normalisation (2006a, 2006b). The database for calculating the LCA was described by Gabrielle et al. (2001). The fuel use and production are expressed as megajoules (MJ) per hectare, and emissions (environmental impacts) as grams (g) of emission equivalents per hectare.

The values for miscanthus management and yield were applicable to France using data and default values from the Institut National de la Recherche Agronomique (INRA) (Gabrielle et al., 2001). We assumed standard agricultural inputs and practices including the use of typical machinery for field preparation, planting, harvest, and transportation, from which we calculated the corresponding emissions using the IFEU standards. Miscanthus plants were presumed to have a useful stand life of sixteen years. Establishment requires two years before the first harvest, followed by a single harvest annually yielding 25 metric tons per hectare (ha). Weed control was required only in the first year, and fertilizing started in the second year at 50 kg per ha of N. Phosphorus and potassium were not added because soil levels were assumed to be adequate, and plant uptake and removal were very low (Lewandowski and Kircherer, 1996). The harvest method was chopping for loose hauling, presuming a loss of plant dry matter of 5%. This compares with 10-30% loss from the round-baling method (ADEME, 1998). Ash disposal to a landfill after combustion was also considered as a byproduct. The environmental impacts of the agricultural production processes were averaged over the lifetime of the crop to obtain annual values. Economic evaluations, not conducted to date, will use discounting.

The fossil fuel life-cycle analysis was carried out similarly to the miscanthus LCA by taking into account all processes involved in resource extraction, processing, and utilization. Natural gas production entailed extraction, transportation, compression, processing, and finally distribution to the consumer. Natural gas was assumed to be extracted in Norway and Russia and distributed throughout France. The crude oil was extracted in OPEC countries and transported to Europe with transport costs calculated using average distances (IFEU, 2000). These choices are based on expert opinion and current technology (IFEU, 2000). The IFEU report provided an assessment of the relative reliability of environmental impacts. Since empirical data were very limited or nonexistent for miscanthus, values were extrapolated from other crop production systems and qualified by in-country experience (Benoît et al., 2001). We decided to analyze only those environmental impacts whose estimates and data sources were considered by IFEU (2000) to be reliable. Impacts excluded from this analysis included stratospheric ozone depletion, human toxicity (e.g. carcinogens, heavy metals, particulates), and ecotoxicity agents (e.g. heavy metals and recalcitrant organics).

For the life-cycle inventory assessment, sums of impacts for all processes were converted into functional units of MJ/ha or g emissions/ha to calculate total impacts for the entire production chain. We subtracted these sums from the reference system for miscanthus. A normalization step, or ranking, was carried out to compare the results over a range of variables and impact categories, including conversion to percentage of total impacts to simplify the presentation and interpretation of data. Calculations and graphing were carried out using Microsoft Excel® spreadsheets.

RESULTS AND DISCUSSION

Standardized outputs of primary energy depletion and environmental pollutants for simulated miscanthus production are illustrated in Fig. 2. All impacts were small in comparison to global warming potential resulting from fertilization, harvest, and transport. Fertilization impact is relatively large because the process of converting atmospheric nitrogen gas (N2) into ammonia is energy intensive and consumes natural gas as a source of hydrogen. Thus, any energy-efficient, plant-derived biofuel system must be one which has very low nitrogen fertilizer requirements. Miscanthus is a crop which is relatively efficient in nitrogen use and conversion to biomass yield (Lewandowski and Schmidt, 2006). Harvest and transport also consume significant amounts of fossil fuel and thus emit measurable amounts of GHG, suggesting the importance of developing improved methods of handling bulky feedstocks such as plant biomass.

The wide range of orders of magnitude of the output values necessitates comparing the two fuels on a percentage basis to more easily visualize their relative impacts. Figure 3 illustrates relative contributions to each impact category of each production process, ranging from seedstock production to ash disposal. The entire value of an impact, be it in MJ of primary energy depletion or g of emissions, is represented by 100%. Combustion contributed the large majority of emissions resulting in ozone creation (photochemical ozone creation potential, POCP, or smog), eutrophication, acidification, global warming potential, and primary energy depletion. The latter category essentially represents fossil-fuel depletion involved in all nonrenewable energy consumption processes. Eutrophication, acidification, and ozone creation are explained by release of nitrogenous, sulfurous, and phosphatic compounds to the soil, water, and atmosphere resulting from fertilization of the crop and from combustion and release of gases (Table 1). Harvest and biomass transport impacted the environment less adversely than fertilization (Fig. 3), whereas seedstock production, field preparation, planting, and pest control contributed negligible amounts to environmental impacts.

Values for comparing miscanthus vs. natural gas are summarized in Table 2. Natural gas had substantially greater resource depletion (3.6-fold) and global warming potential (2.0-fold) than miscanthus. Photochemical ozone creation potential was essentially the same between the two energy sources. In contrast, acidification and eutrophication impact values were lower and thus more favorable for natural gas than miscanthus, based on our analyzed system. The calculated differences between the fuel types indicate which had a more favorable environmental impact. The negative values represent an advantage for the bioenergy when compared to its fossil fuel counterpart. Likewise, positive values show a disadvantage for the biofuel. Results are also presented as relative percentages of the sum of the two energy types (Fig. 4). This presentation normalizes the data and places the impact categories on the same scale. The advantage of miscanthus over natural gas in reducing nonrenewable resource depletion and global warming potential is again clear, as is the relative advantage of natural gas in reducing acidification and eutrophication.

It is clear that replacing a nonrenewable fossil fuel such as natural gas with a renewable, perennial biofuel crop would greatly reduce depletion of fossil fuel reserves, even though some fossil energy consumption occurs with production, harvest, and transport of the crop. The annual photosynthetic ability of miscanthus greatly reduces net CO_2 emissions and thus reduces GHGs and the global warming potential. Lewandowski et al. (1995) concluded that combusting 20 metric tons/ha miscanthus emits a net 2.2 tons CO_2, whereas combusting the same energy equivalent of hard coal emits 34 tons CO_2. Therefore each hectare of miscanthus would directly reduce emission of 31 tons CO_2 per year (90% reduction) when compared with hard coal. In addition to CO_2, emissions include other GHGs such as CO, CH_4, and N_2O (Kaltschmitt et al., 1997). Use of low-net-emission biofuels combined with minimal fossil energy consumption during conversion would have more favorable effects on atmospheric conditions, particularly global warming reduction, than any fossil fuel.

The disadvantage of miscanthus in terms of acidification and eutrophication demonstrates that biofuel crops are not completely benign in their potential environmental impact when used in combustion. Sources of emissions in these categories are mainly from the combustion process itself (Fig. 3), which oxidizes organic S and N in plant biomass to SO_2, NO_x, and other trace compounds, which convert to acids in the atmospheric water and return to soil and surface waters as precipitation or dry fallout. Natural gas is a relatively clean-burning fossil fuel, especially in relation to coal. Soil acidification from nitrogen fertilizer was assumed to occur in this LCA, and fertilization of the biofuel crop to produce high yields results in some degree of leakage of nutrients off-site. The ability of miscanthus to retain and internally recycle environmentally sensitive macronutrients such as N, P, and S is poorly understood. Efficient nutrient recycling of such nutrients would be expected to minimize the eutrophication impact of producing perennial biofuel crops.

Conclusions

We conclude that the lignocellulosic feedstock, miscanthus, is a more environmentally beneficial fuel source than natural gas in terms of global warming potential when comparing their use for combustion for district heating. Miscanthus production would theoretically involve zero net carbon emissions when only considering the re-assimilation of CO_2 via photosynthesis that had been previously emitted through combustion; however, use of fossil fuels in nitrogen fertilizer synthesis, delivery, and application and the harvest and transport of biomass consume some fossil energy. Site conditions, nitrogen fertilizer-use efficiencies by different feedstocks, and local economic factors must be taken into account when selecting a fuel source that will create the most environmentally benign system. The agronomic properties of miscanthus make it a promising plant species for bioenergy in France and potentially the U.S. because it produces high biomass yields with a low level of industrial inputs, such as fertilizers and pesticides. The favorable CO_2 balance of this feedstock emphasizes its efficiency as a fuel source, especially considering current global climate change. It is important to note that other biomass species, such as switchgrass (*Panicum virgatum*), may lead to different results if our assumptions do not apply. The comparison of biogenic and fossil fuels shows clear advantages and disadvantages with both fuel options, and decision-makers must consider the trade-offs based on the acceptance of the various ecological impacts on a worldwide basis.

Further research should include field trials and comparative analyses with other biofuel feedstocks in multiple sites in Europe and the U.S. to more accurately quantify the net energy balances and environmental impacts than just those estimated in this simulation model. Life-cycle analyses are useful complements to field trials to estimate environmental advantages of alternative biofeedstocks that could replace nonrenewable fossil fuels.

ACKNOWLEDGMENTS

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Table 1. Impact classification of pollutants indexed in the life cycle inventory.

Impact categories	Pollutants inventory
Primary energy depletion	Primary energy inputs: natural gas, petroleum, coal, and uranium
Global warming potential (GWP)	Volatile organic compounds (VOCs) CO_2, CO N_2O, CH_4
Ozone depletion	N_2O
Photochemical ozone creation potential (POCP, smog)	Benzene (C_6H_6), Methane (CH_4), VOCs CO, Hexane
Acidification	NH_3, HCl, NO_x, SO_2
Eutrophication	NO_x, NO_3^-, NH_3, NH_4^+, PO_4^{-3}

Table 2. Resource depletion and emission values for miscanthus and natural gas. Negative values for the difference between the energy types indicate an environmental benefit from using the bioenergy crop over the fossil fuel.

Environmental impact	Balance parameter	Unit (per hectare, per year, per MJ of heat)	Bioenergy life cycle (miscanthus)	Fossil fuel life cycle (natural gas)	Difference (bioenergy-fossil fuel)
Resource depletion	Primary energy	MJ	0.3415	1.2336	-0.8921
GWP500	CO_2 equivalents	g	35.128	69.814	-34.685
POCP	Ethylene equivalents	g	0.0182	0.0199	-0.0017
Acidification	SO_2 equivalents	g	0.2910	0.0601	0.23090
Eutrophication	NO_3 equivalents	g	0.3092	0.0785	0.2306

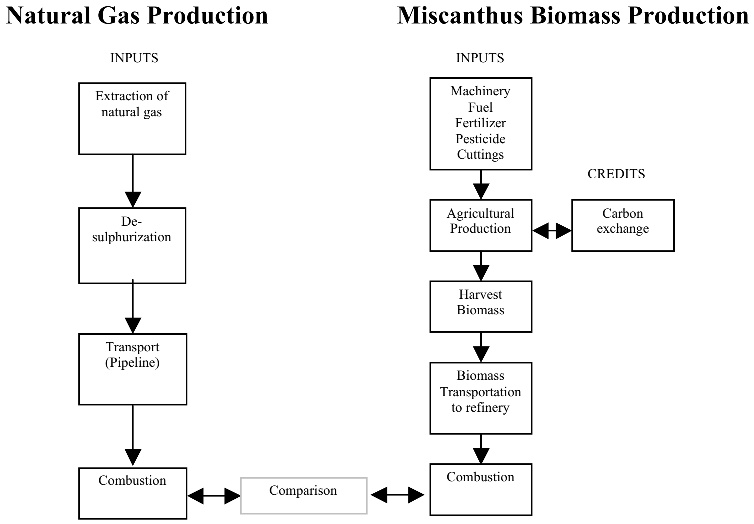

Fig. 1. Standard life cycle comparison of natural gas and miscanthus production

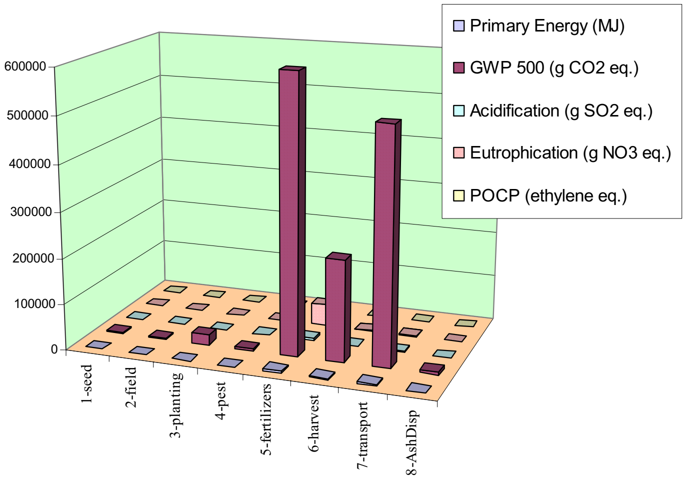

Fig. 2. Impacts of miscanthus production steps on environmental impact categories expressed as standardized functional units, megajoules (MJ) or grams (g) per hectare, as appropriate.

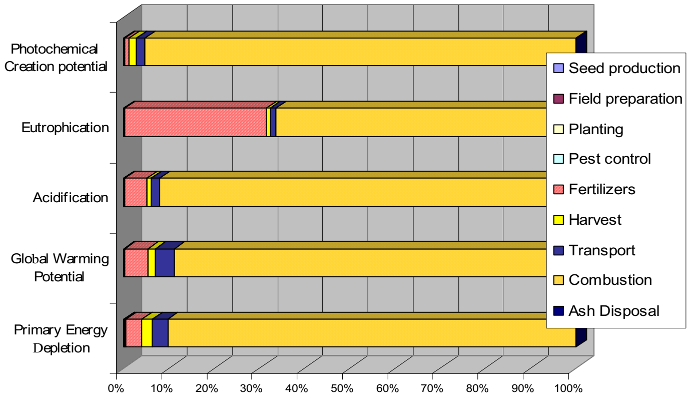

Fig. 3. Relative contributions of miscanthus biofuel production and combustion processes to each environmental impact classification.

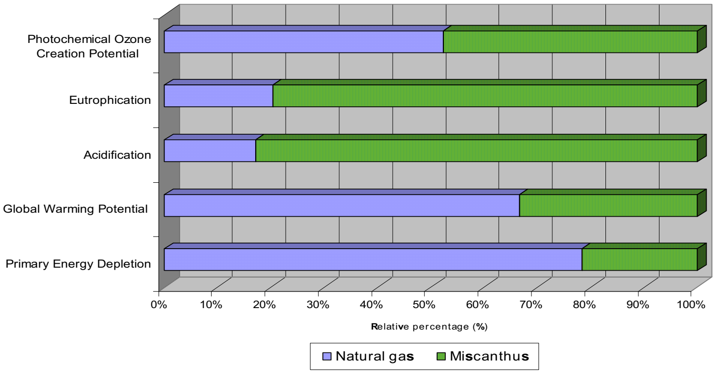

FIG. 4. Comparisons of miscanthus vs. natural gas for their environmental impacts. Fuel type with a horizontal bar greater than 50% indicates more negative environmental impact.