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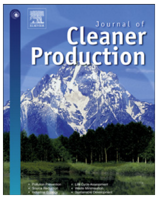

Environmental impact assessment of regional switchgrass feedstock production comparing nitrogen input scenarios and legume-intercropping systems

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ABSTRACT

As the use of second-generation biofuel crops increases, so do questions about sustainability, particularly their potential to affect fossil energy consumption and greenhouse gas emissions. This study used a life-cycle approach to compare environmental impacts associated with three switchgrass (*Panicum virgatum* L.) production scenarios: i) regional production from a pool of Tennessee farmers based on in-field inputs and biomass yield; ii) varying nitrogen (N)-input levels from a replicated field study for 8-yrs i.e., a 100% and 9% decrease, and an 81% and 172% increase from 'baseline levels' of N inputs used under objective i; and, iii) a legume-intercrop system compared to baseline levels in order to determine effects of displacing synthetic-N with legumes. When compared across all agricultural inputs, nitrogen fertilizer production and breakdown resulted in the greatest environmental impacts. Although fertilization increased lignocellulosic yields, a 100% reduction in N-inputs from baseline levels reduced the formation of carbon, methane, and nitrous oxides per *unit of production*, (or dry tonne of biomass over 10-yrs) compared to a 172% increase. Switchgrass yield response indicated a 'less is more' scenario, as inputs beyond the current recommended input level (67 kg N ha^{-1}) are not environmentally remunerating. During switchgrass biomass production, inputs with lesser impacts included phosphorus, herbicides, pesticides, and diesel fuel. Legume-intercropping reduced greenhouse gas emissions and groundwater acidification (5% and 27% reduction in global warming potential and formation of acidifying species, respectively) compared with the 67 kg N ha^{-1}rate. Although N-fertilizers impact environmental sustainability of regional switchgrass feedstock production, environmental consequences can be reduced under proper N-management i.e., $\leq$67 kg N ha^{-1} or legume intercropping. However, given that the aim of second-generation feedstocks is to reduce the current reliance on fossil fuels, their production still requires fossil energy-based inputs. Consequently, greenhouse gas reductions and the extent of cleaner feedstock production during the agricultural biofuel supply chain is contingent upon input management and optimizing synthetic fertilizer usage.

1. Introduction

There are growing concerns about the environmental sustainability of feedstocks, specifically input requirements and their relationship to the amount and value of the outputs. One tool for evaluating system environmental sustainability is life-cycle assessment (LCA), which measures inputs to and emissions from production life cycles (Cherubini and Jungmeier, 2010). In addition,

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Acronyms: LCA, life cycle assessment; GWP, global warming potential; GHG, greenhouse gas.

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as much as 21.3 million ha of existing agricultural land in the U.S. may be converted to perennial grass feedstocks (McLaughlin et al., 2002), thereby making regionally-specific environmental sustainability measurements, such as LCA, critical before large-scale adoption of a second-generation feedstock.

Life-cycle assessments include life cycle inventories and life cycle impact assessments (ISO, 2006). Life-cycle inventory (LCI) is an accounting of the energy and raw material inputs, as well as emissions to air, water, and soil (ISO, 2006). The life cycle impact assessment (LCIA) process characterizes and calculates the effects of emissions identified in the LCI into generalized impact categories. Impact categories at the midpoint level characterize impacts using indicators located along (but before the end of) the mechanism chain [e.g., parameter in a cause-effect network between the inventory data and the category endpoints (Bare et al., 2000; ISO, 2006)]. Examples of midpoint impact categories that are commonly used are global warming potential (GWP), photochemical ozone creation potential [POCP (i.e., smog)], acidification, eutrophication, and ozone depletion (NREL, 2011). Impacts of various production scenarios can be compared and thus LCA can be used to identify options that reduce a system's environmental impacts.

The majority of biofuel-focused LCAs have found a significant reduction in greenhouse gas (GHG) emissions from second-generation feedstocks, such as switchgrass, when compared with their conventional fossil fuel or first-generation counterparts [i.e., corn-(*Zea mays* L.)-ethanol] (Blottnitz and Curran, 2007; Cherubini and Jungmeier, 2010; Kim and Dale, 2005). The Brazilian paradigm for ethanol production [i.e. fermentation of sugarcane (*Saccharurn officinarum* L.)] is reportedly the highest performing first-generation biofuel crop in terms of environmental sustainability, and may exceed that of some second-generation feedstocks (Kendall and Yuan, 2013). However, composited, peer-reviewed LCAs determined that among all fuel pathways expected to contribute substantially to the U.S's renewable fuel portfolio, switchgrass-ethanol offered the greatest reduction in GHG emissions when compared to other fuel pathways [i.e., corn-ethanol, soy-(*Glycine max* L.) based biodiesel, waste/grease biodiesel, and sugarcane -ethanol] (Adler et al., 2007; EPA, 2009). In these analyses, switchgrass-ethanol resulted in a 124% and 128% reduction in GHG emissions (compared to a gasoline baseline) under two scenarios: 30 year, 0% Discount Rate (i.e., values all emission impacts equally, regardless of time of emission impact); and 100 year, 2% Discount Rate (discounts future emissions annually at 2%), respectively (EPA, 2009).

Net energy analyses have been used to evaluate fossil fuel and cellulosic biofuel-energy efficiencies. Reed et al. (2012) constructed an LCI of switchgrass fuel pellets based on surveys of switchgrass farmers and wood pellet producers in the southeastern U.S. and concluded that energy produced in switchgrass pellets was five times greater than the total fossil energy consumed to create them. Schmer et al. (2008) reported that switchgrass biomass yields ranging from 5.2 to 11.1 Mg ha^{-1} resulted in an average estimated net energy yield (NEY; or energy output ha^{-1} minus fossil energy input ha^{-1}) of 60 GJ ha^{-1} yr^{-1} or 6.4 times more renewable energy than the non-renewable energy consumed. This study, as well as previous models [e.g., Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) and the Energy and Resources Group (ERG) Biofuel Analysis Meta-Model (EBAMM)], assume a linear response of switchgrass yields to agricultural inputs. However, the majority of long-term field research indicates yield response reaches an asymptote before 134 kg nitrogen (N) ha^{-1}, with an inflection point being reached at 67 kg ha^{-1} (Mooney et al., 2009). Other studies have reported negative energy balances for switchgrass-based ethanol under assumptions of high levels of inputs (Pimentel et al., 2008); however, such assumptions are made without regionally measured plant-response values. Data are lacking that document specific environmental impacts from regional on-farm switchgrass production, especially impacts resulting from fertilization. Therefore, by evaluating impacts from varying fertilizer levels, the feasibility of environmentally sustainable feedstock production may be elucidated.

Production of second-generation biofuels may still result in acidification and ozone depletion due to use of synthetic fertilizers (compounds based on N and P) and pesticides (Larson, 2005; Zah et al., 2007). Nitrogen is an essential macronutrient in cropping systems but N emissions from its breakdown and production (e.g. nitrous oxide) are assumedly major contributors to GWP, acidification, and eutrophication in LCA simulations. Therefore, a positive result in one part of the cropping life cycle (i.e., increased crop yield) may be associated with a negative result (i.e. increased acidification) in another. However, there is a range of differences in production patterns and systems, as well as cultural practices, which makes regional and processing differences great (Ruviaro et al., 2012). Furthermore, the majority of LCAs conducted have been based on national or state-wide systems rather than on regional primary (enterprise-level) production data. Such regionally parameterized analyses of feedstock production are needed in order to more accurately model impacts of regional bioethanol production systems, albeit such specificity may preclude wide-scale assertions and recommendations.

A joint venture between the University of Tennessee, and DuPont Danisco Cellulosic Ethanol [i.e., University of Tennessee Biofuels Initiative (UTBI[1])] established the nation's first pilot-scale, demonstration cellulosic biorefinery for the conversion of switchgrass to ethanol. This biorefinery, located in Vonore, Tennessee could require up to 154 tonnes of switchgrass per day and produce 19 million liters of ethanol per year (DOE, 2007). Since 2010, approximately 2100 ha of switchgrass have been planted, all of which are located within 80 km of the Vonore plant, making this the nation's first and largest switchgrass cellulosic ethanol venture. The study reported herein used: i) farm production-level field data from the UTBI project for modeling energetic efficiencies of switchgrass production, ii) an 8-yr, four sites field-study of four different N-fertilization rates on switchgrass biomass yield for a sensitivity analysis, and iii) a 4-yr replicated field study of intercropping legumes with switchgrass for biomass production as a replacement for the 'baseline N fertilization rate' used in objective i. Specifically, study objectives were to: i) identify the potential environmental impacts associated with farm-derived regional switchgrass production based on in-field agricultural input levels and biomass tonnage from a regional pool of farmers with the UTBI; ii) quantify environmental impacts as a function of decreasing or increasing N input levels. [i.e., a 100% and 9% decrease, and a 81% and 172% increase] compared to the baseline level of N input under objective i; and, iii) compare legume-intercrop systems to baseline results in order to determine the effects of displacing synthetic-N with intercropped legumes that host N-fixation.

2. Methods

This study applied LCA principles to evaluate environmental impacts of switchgrass grown under various scenarios. Cradle-to-gate LCI was developed (Reed, 2012) and LCIA used to compare production scenarios. This report is not however intended to present a complete LCA in full compliance with the ISO standards.

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[1] http://www.tennessee.edu/media/kits/biorefinery/docs/utbis_overview.pdf.