Environmental and Sustainability Factors Associated With Next-Generation Biofuels in the U.S.: What Do We Really Know?

PAMELA R. D. WILLIAMS,*,† DANIEL INMAN,‡ ANDY ADEN,‡ AND GARVIN A. HEATH§

E Risk Sciences, LLP, 4647 Carter Trail, Boulder, Colorado 80301, National BioEnergy Center, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado, and Strategic Energy Analysis Center, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado

Received January 23, 2009. Revised manuscript received April 26, 2009. Accepted May 6, 2009.

In this paper, we assess what is known or anticipated about environmental and sustainability factors associated with next-generation biofuels relative to the primary conventional biofuels (i.e., corn grain-based ethanol and soybean-based diesel) in the United States during feedstock production and conversion processes. Factors considered include greenhouse (GHG) emissions, air pollutant emissions, soil health and quality, water use and water quality, wastewater and solid waste streams, and biodiversity and land-use changes. Based on our review of the available literature, we find that the production of next-generation feedstocks in the U.S. (e.g., municipal solid waste, forest residues, dedicated energy crops, microalgae) are expected to fare better than corn-grain or soybean production on most of these factors, although the magnitude of these differences may vary significantly among feedstocks. Ethanol produced using a biochemical or thermochemical conversion platform is expected to result in fewer GHG and air pollutant emissions, but to have similar or potentially greater water demands and solid waste streams than conventional ethanol biorefineries in the U.S. However, these conversion-related differences are likely to be small, particularly relative to those associated with feedstock production. Modeling performed for illustrative purposes and to allow for standardized quantitative comparisons across feedstocks and conversion technologies generally confirms the findings from the literature. Despite current expectations, significant uncertainty remains regarding how well next-generation biofuels will fare on different environmental and sustainability factors when produced on a commercial scale in the U.S. Additional research is needed in several broad areas including quantifying impacts, designing standardized metrics and approaches, and developing decision-support tools to identify and quantify environmental trade-offs and ensure sustainable biofuels production.

* Corresponding author phone: 303-284-1935; e-mail: pwilliams@erisksciences.com.

† E Risk Sciences, LLP.

‡ National BioEnergy Center.

§ Strategic Energy Analysis Center.

Introduction

Modern liquid biofuels are promoted in the United States (U.S.) as a means of achieving national energy independence and security and reducing greenhouse gas (GHG) emissions (*1–5*). First-generation (i.e., conventional) biofuels in the U.S. are produced primarily from major commercial crops such as corn (*Zea mays, L.*)-grain ethanol and soybean (*Glycine mix, L.*) biodiesel (*6, 7*). Under the U.S. Energy and Independence Security Act of 2007, conventional biofuel production is permitted to increase through 2015 up to the 15 billion gallon per year cap set on corn-grain ethanol (*4*). However, issues of sustainability and environmental impacts have been raised in response to the wide-scale production and use of conventional biofuels. For example, traditional intensive corn-grain and soybean production practices are associated with high rates of chemical (e.g., fertilizer, pesticide) inputs, extensive water consumption in some regions, and many deleterious environmental effects such as soil erosion, surface water pollution, air pollution, and biodiversity losses (*8–13*). Furthermore, recent studies suggest that increased biofuel production, particularly conventional biofuels, could result in a substantial "carbon debt" because the quantity of carbon dioxide (CO_2) released from direct and indirect land-use changes will be far greater than the GHG reductions from the displacement of fossil fuels (*14, 15*). Although some have been critical of these studies (*16, 17*), and advances in agronomy and biofuel conversion efficiencies have been noted (*12, 18, 19*), the expansion of conventional annual crops for biofuels may still have negative long-term environmental consequences unless more sustainable practices are employed (*10, 20*).

The desire for more diverse and sustainable fuel sources has led to greater attention being focused in the U.S. on second- and third-generation (i.e., next-generation) liquid biofuels which are produced through a variety of feedstocks and conversion technologies (*7, 21–25*). Although the literature suggests that next-generation biofuels have the potential to avoid many of the environmental challenges that face conventional biofuels (*9, 10, 15, 26–28*), few attempts have been made to synthesize and document the current state-of-knowledge on how the production of next-generation biofuels compares to conventional biofuels. The purpose of this paper is 2-fold: (1) qualitatively summarize the literature in regard to what is known or anticipated about environ-

10.1021/es900250d CCC: $40.75
Published on Web 05/27/2009

mental and sustainability factors associated with next-generation biofuels relative to the primary conventional biofuels in the U.S. from a high-level perspective; and (2) quantitatively estimate environmental emissions, water consumption, and waste streams during selected feedstock production and ethanol conversion processes using life-cycle assessment (LCA) and systems engineering modeling tools as illustrative examples. We focus on biofuels in the U.S. context, though many of the research findings are applicable to other locations. Environmental and sustainability factors considered here include GHG emissions, air pollutant emissions, soil health and quality, water use and water quality, wastewater and solid waste streams, and biodiversity and land-use changes. Note that these factors relate primarily to environmental releases rather than impacts, because the available data and modeling tools are insufficient to adequately characterize the ultimate outcomes (e.g., human morbidity or mortality, species loss) associated with next-generation biofuels. As part of our review and analysis, we also identify several key data gaps and important areas for future research.

Our reference point for comparison is U.S.-based conventional liquid biofuels (i.e., corn-grain ethanol and soybean biodiesel); comparison to petroleum-based fuel is beyond the scope of this study. Additionally, the current paper is specifically focused on feedstock production and fuel conversion because these two life-cycle stages are considered the most significant overall with regard to environmental implications and are likely to result in the greatest differences between conventional and next-generation biofuels. In this study, next-generation feedstocks are categorized as follows: (1) the cellulosic components of municipal solid waste (e.g., tree trimmings, yard waste, paper products), (2) forest residues and thinnings (e.g., logging residues from commercial forests), (3) annual crop residues (e.g., corn stover), (4) dedicated herbaceous perennial energy crops (e.g., switchgrass, Miscanthus, native prairie grasses), (5) short-rotation woody crops (e.g., hybrid poplar, willow shrubs, eucalyptus), and (6) microalgae. These feedstocks can produce a variety of liquid transportation fuels (e.g., ethanol, biodiesel, jet fuel, green gasoline, green diesel), although feedstock categories 1−5 are typically associated with the production of ethanol while category 6 is generally associated with the production of biodiesel. Other oil-bearing feedstocks such as Jatropha (*Jatropha curcus L.*), grease and cooking waste oil, and animal fats, are not included in this study because they are of greater international interest or are not considered capable of making a significant contribution to the U.S. biofuel market (*29*−*31*). Two next-generation conversion technologies are considered in this study: (1) ethanol produced via a biochemical (enzymatic or acid hydrolysis) process, and (2) ethanol produced via a thermochemical (gasification) process. Algae-based biodiesel conversion is not discussed because transesterification is a mature and well-known process (*32*). Advanced hybrid conversion platforms and pyrolysis technologies are also not discussed due to limited access to information on these technologies. Factors related to net energy, feedstock and conversion yields, socio-economic impacts, and public policy are outside the scope of the current paper.

Methods

This study employed two strategies: (1) a qualitative high-level review of the current literature and (2) quantitative illustrative estimates of environmental emissions, waste streams, and water consumption based on modeling. The literature review portion of this study was conducted using standard search techniques such as Boolean searches of relevant databases (e.g., Web of Science, Agricola). In addition to reviewing the peer-reviewed literature, federal government reports, presentations, and workshop materials were gathered. Personal interviews were conducted with relevant experts within the federal government, national laboratories, and selected universities. Meetings held by the interagency Biomass R&D Board, which was created by Congress in 2000 to coordinate federal activities and promote the development and adoption of biobased fuels and products in the U.S., as well as its working groups on Sustainability and Feedstock Production, were also routinely attended. Additionally, feedstock field trials and cellulosic pilot and/or proposed commercial biorefineries were toured. Based on the information gathered from these sources, next-generation biofuels are qualitatively summarized and compared to the primary conventional biofuels in the U.S. across a range of environmental and sustainability factors. Quantitative estimates are also presented in some instances to provide greater context, but precise values were not deemed to be feasible for most factors due to the paucity of data on different feedstocks, technologies, and scenarios and the difficultly in making comparisons among diverse studies. Life-cycle stages considered during feedstock production include the production of farm or field inputs, field preparation activities, planting and establishment activities, and feedstock harvesting and collection. Life-cycle stages considered during ethanol conversion include the amount and source of energy used in the biorefinery, the production of chemical and other biorefinery inputs, and the conversion process itself.

The second portion of this study utilized certain modeling tools to illustratively estimate and compare potential environmental emissions, waste streams, and water consumption associated with feedstock production and ethanol conversion. These modeling approaches are briefly described below, with a more detailed description presented in the online Supporting Information. For feedstock production, the SimaPro (v. 7.1.8) LCA model (www.pre.nl/simapro/) is used to make comparisons between three next-generation feedstocks (corn stover, switchgrass, and forest residues) and corn grain. The life-cycle stages included in this modeling are the same as those considered in the literature review. Factors assessed during feedstock production are GHGs, air pollutants, water use, and water quality metrics. For ethanol conversion, the Advanced Simulator for Process Engineering Plus (AspenPlus) model (www.aspentech.com/core/aspen-plus.cfm) is used to make predictions for biochemical and thermochemical conversion platforms for the same three next-generation feedstocks. Corn-grain ethanol is not modeled due to the lack of a comparable AspenPlus model for this feedstock. The only life-cycle stage included in this modeling is the conversion process itself (i.e., other stages were not assessed because the AspenPlus model is a mass-balance, not a LCA, model). Factors assessed during ethanol conversion are GHGs, air pollutants, water use, wastewater, and solid waste streams. Note that the modeling performed in this study is not intended to be comprehensive, but rather is for illustrative purposes and to provide more quantitative and comparative information than a traditional literature review (i.e., the modeling allows for more direct, quantitative comparisons using standardized platforms and consistent system boundaries and assumptions).

Results

The following sections summarize the current state-of-knowledge of environmental and sustainability factors associated with next-generation biofuels relative to conventional biofuels based on our qualitative review of the literature and quantitative modeling analyses. Results are provided separately for feedstock production and conversion stages.

Feedstock Production—Literature Review. Overall, the production of next-generation feedstocks is expected to fare better than conventional biofuel feedstock production on most environmental and sustainability factors. The specific comparisons focused on here are between next-generation feedstocks and conventional feedstocks that are currently associated with the same biofuel in the U.S.; i.e., municipal solid waste (MSW), forest residues and thinnings, crop residues, dedicated herbaceous perennial energy crops, and short-rotation woody crops (SRWC) are compared to conventional corn-grain production, while microalgae is compared to conventional soybean production. However, because none of the next-generation feedstocks are currently produced or collected on a commercial scale, there is significant uncertainty regarding their potential positive or negative environmental implications. In particular, the sustainability of any feedstock is dependent on many factors including prior and future land use, production and management practices, temporal and spatial considerations, and prevailing environmental conditions (e.g., soils, climate) (*10, 33, 34*). There is also considerable debate about whether or how to allocate life-cycle environmental burdens between products, and the choice of allocation method can have a significant influence on the results of a study (*35, 36*). For example, in one LCA of ethanol derived from MSW, none of the environmental burdens associated with the processes and products that generated the MSW were allocated to MSW because it was assumed that MSW was a waste that needed to be disposed of (*37*). On the other hand, in LCAs of ethanol produced from corn stover, allocation schemes have ranged from attributing all life-cycle burdens of producing corn grain to the corn stover (*38*) to attributing none of these burdens to corn stover (*39*). While these are all important issues, an in-depth discussion of influential factors and allocation methodologies for different feedstocks is beyond the scope of this paper.

GHG Emissions. The production of next-generation feedstocks is generally expected to result in fewer overall GHG emissions compared to conventional corn-grain or soybean production in the U.S (*9, 10, 26, 27, 40*). In particular, next-generation feedstocks such as waste biomass and biomass grown on uncultivated land (i.e., unutilized arable or marginal land) are projected to incur little or no carbon debt (*14*). Anticipated reductions in GHG emissions compared to conventional feedstocks are driven primarily by the following: (1) less significant land-use/conversion impacts; (2) greater carbon sequestration in soil, plant, and root systems; (3) fewer fertilizer and pesticide inputs; and (4) less energy-intensive management practices. Reduced nitrogen fertilizer use is particularly beneficial because of reduced nitrous oxide (N_2O) emissions, which are 310× more potent than CO_2 as a GHG, and N_2O releases can easily offset carbon sequestration gains (*12, 41*).

Depending on how upstream environmental burdens are allocated, the collection of waste biomass and residues for use as feedstocks may be especially promising because they are not produced *per se*, but rather are diverted from waste streams that might be disposed of in different ways. For example, because MSW is often destined for landfills, using the biological fraction of MSW as a feedstock for biofuels has the potential to emit significantly lower GHGs than conventional corn-grain production which generally requires significant amounts of land, energy, and chemical inputs (*37, 42*). Life-cycle GHG emissions from MSW-based ethanol are estimated to be approximately 60−80% less than that of conventional corn-grain ethanol, and presorting of marketable aluminum, glass, steel, and plastic materials can reduce GHG emissions by approximately 50% compared to unsorted MSW-based ethanol (*37*). It is currently unclear to what extent the allocation of potential upstream burdens associated with MSW (e.g., grass clippings produced from fertilized lawns) might offset these GHG reductions.

Similarly, using forest residues and thinnings from existing commercial logging operations as a feedstock has the potential for much lower GHG emissions compared to conventional corn-grain production because these feedstocks are considered nonmerchantable products of existing forest production systems. The collection of forest residues and thinnings has the added benefit of avoiding GHG emissions related to intentional burnings (i.e., forest residues are often disposed of through burnings) and forest wildfires (i.e., removing thinnings may reduce the frequency and intensity of wildfires) (*43*−*46*). Although logging activities (e.g., felling, skidding, delimbing) and residue processing (e.g., loading, chipping) are energy-intensive, total fossil fuel consumption and CO_2 emissions are likely to be much lower per ton of feedstock than corn-grain production given the large volumes of potentially available biomass. Additionally, even if some of the potential upstream burdens due to conventional commercial forestry (e.g., intensive land preparation, energy-intensive machinery, large pesticides and fertilizer inputs) are allocated to forest residues and thinnings, such burdens only need to be considered during forest seeding and re-establishment phases (i.e., once every 40−75 years) (*47*).

The use of crop residues, such as corn stover, as a feedstock is also expected to result in lower GHG emissions relative to conventional corn-grain production because these residues are a coproduct of existing crop production systems (although the magnitude of such GHG reductions is dependent on allocation method). However, some research suggests that the removal of corn stover could increase the net rate of CO_2 emissions during agricultural activities unless "best practices" are used because crop residues provide cover that allows for greater soil carbon retention rates (*48*). Additional fertilizer (e.g., 16 pounds of nitrogen per ton of dry matter) may also be required to replace nutrients during stover harvesting (*38, 49*). GHG emissions may also occur during the collection of crop residues after corn harvesting unless equipment capable of performing a single-pass harvest becomes commercially available (*38, 45*).

The production of dedicated perennial herbaceous energy crops is expected to result in lower GHG emissions than conventional corn-grain production, particularly if these crops are grown on uncultivated land, because it is anticipated that such production will require fewer pesticide and fertilizer inputs and less intensive tillage practices (*9, 10, 26, 45, 50*−*58*). The production of these crops on currently cultivated agricultural land, however, could result in additional GHG emissions from indirect land-use changes (*15*). Some dedicated herbaceous energy crops that are intensively managed as a monoculture may also require significant pesticide and fertilizer inputs and research suggests that these crops could be grown more sustainably as polycultures (*9, 10, 51, 53, 59*). Because dedicated herbaceous energy crops are grown for durations as long as a decade or more per rotation, they provide year-round soil cover and develop deep and complex root systems that sequester significant amounts of carbon underground (*54, 57, 60*). For example, carbon sequestration rates have been found to be as high as 20−30× greater for perennial grasses such as switchgrass compared to annual row crops like corn (*57*), and experiments with mixtures of native grassland perennials have shown that low-input high-diversity plots can result in 30× greater CO_2 sequestration in soil and roots relative to monoculture plots (*53*). Additionally, if nitrogen fertilizer is applied to perennial energy crops it has the potential to be less susceptible to denitrification and N_2O emissions than conventionally grown corn that is irrigated because the use of irrigation is minimal or nonexistent for these crops (i.e., water mediates denitrification) and there is a longer time frame during which fertilizer can be applied (i.e., this allows for better timing of fertilizer applications to drier conditions). Relative to corn, switchgrass

(*Panicum Virgatum*, L.), miscanthus (*Miscanthus x giganteus*), and native prairie grasses have higher nitrogen-use efficiency (i.e., amount of nitrogen taken up and used in the plant per amount applied) because plant nitrogen is translocated to the roots during senescence where it is stored over winter; this results in less nitrogen fertilizer applied and therefore less potential for N_2O emissions (*9, 51, 54, 55, 57, 61, 62*). Studies indicate that switchgrass production requires approximately 25−50% less total nitrogen use than conventional corn-grain production, although actual nitrogen application rates will vary depending on region and desired yields (*57, 59, 63, 64*). GHG emissions related to the production of SRWC are expected to be similar to those of dedicated herbaceous energy crops for the reasons mentioned above (*9, 26, 52, 65, 66*). Research also suggests that SRWC can store substantial amounts of carbon in roots and soil (*66*). As with forest residues, the harvesting and processing of SRWC is fossil fuel-intensive, but GHGs emitted during these activities are likely to be outweighed by the GHG emission reductions associated with SRWC production relative to conventional corn-grain production.

The cultivation of microalgae is expected to use approximately 100−300× less land area per unit yield than conventional soybean production, and it is anticipated that microalgae production will not require arable land or land applications of pesticides and fertilizers for open ponds or closed bioreactors (obviating indirect land-use GHG emissions) (*9, 26, 29, 30, 67−70*). Unlike most other crop-based feedstocks, microalgae may also be able to utilize nutrient-laden wastewater for cultivation, thus negating the need for fertilizers produced using fossil energy and avoiding the need to treat said wastewater (*29, 71*). Furthermore, studies indicate that CO_2 fixation (i.e., the capacity to absorb CO_2 in biomass) is approximately 10−50× greater for microalgae than terrestrial plants (*29, 71, 72*). Microalgae require CO_2 to grow, which could be provided by local industrial CO_2 sources (e.g., power plants), thus providing a GHG emission mitigation option for those sources (*9, 30, 67, 71, 73, 74*). However, some studies have shown that microalgae harvesting and separating is very energy intensive and requires significant chemical inputs (*69, 71, 75*). On balance, based on the current state-of-knowledge, potential GHG emissions from microalgae operational activities are likely to be outweighed by the GHG emission reductions associated with the production efficiency and sequestration potential of microalgae relative to conventional soybean production.

Air Pollutant Emissions. The production of most next-generation feedstocks is expected to result in fewer direct air pollutant emissions (or secondary transformation products) than conventional corn-grain or soybean production due to the use of waste products and less intensive agricultural production practices, particularly if grown on uncultivated land (see prior discussion). However, according to a recent LCA study, MSW-based ethanol is estimated to result in 44% greater volatile organic compound (VOC) emissions, 5−6% greater carbon monoxide (CO) emissions, 13−38% greater NO_x emissions, 18% greater particulate matter (PM_{10}) emissions, and 32−141% greater sulfur oxide (SO_x) emissions compared to corn-grain ethanol, but it is unclear what proportion of these emissions is attributable to feedstock production relative to other life-cycle stages (*37*). Because they are typically treated as waste products, the use of forest residues and thinnings is likely to decrease overall air pollutant emissions compared to conventional corn-grain production (except perhaps during forest seeding and re-establishment), and some studies suggest that the collection of forest residues and thinnings can reduce local and regional air pollution by avoiding the intentional burning of logging residues and reducing the frequency and intensity of wildfires, respectively (*45, 46*). Similarly, depending on allocation method, using crop residues as a feedstock is generally expected to result in lower air pollutant emissions relative to corn-grain production, although additional fertilizer may be required to replace removed nutrients (see above). Note that in one LCA of ethanol produced from corn stover, this feedstock was found to yield 9× higher nitrogen oxide (NO_x) emissions compared to conventional gasoline, primarily due to emissions from cultivated soil (*38*).

The production of dedicated herbaceous energy crops and SRWC is also likely to result in lower air pollutant emissions than conventional corn-grain production due to anticipated lower pesticide, fertilizer, and tillage requirements. A recent study found that growing perennial biomass crops on land currently in the U.S. Conservation Reserve Program (CRP) results in lower fine particulate matter ($PM_{2.5}$) concentrations than corn grown conventionally in the same region because of lower fossil fuel and fertilizer inputs (*58*). Additionally, large-scale switchgrass production has the potential to reduce regional concentrations of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) because more efficient uptake of nitrogen by switchgrass compared to corn means lower fertilizer demand and fewer field applications (*39*).

Although exact future production methods are highly uncertain, the cultivation of microalgae is expected to emit only carbon and hydrogen, thus greatly reducing air emissions of sulfur and nitrogen-containing compounds compared to conventional soybean production (*68*). Several microalgae species have also been found to tolerate moderate levels (up to 150 ppm) of SO_x and NO_x present in industrial flue gas, which is a potential source of CO_2 needed by the microalgae (*71*).

Soil Health and Quality. Soil organic carbon (SOC) and soil erosion potential are important measures of soil health and quality. Soil properties such as cation exchange capacity, water holding capacity, soil structure, and root penetration are directly affected by SOC levels (*76−78*). Soil erosion reduces productivity through the loss of water-holding capacity and nutrients (*79*). Most studies show that these measures of soil health are affected by crop management practices (e.g., tillage, rotation, fertilization), although recent research suggests SOC levels for the entire soil profile (>1m) are not significantly different between tillage practices (*76, 79−82*). While there is currently debate regarding the relationship between tillage and SOC, there are other compelling reasons to practice conservation tillage, such as reduced erosion potential and lower fossil fuel use. In general, SOC levels are highest for forest lands and the lowest for croplands, with dedicated herbaceous energy crops and SRWCs falling between these extremes (*78*).

Crop residues notwithstanding, next-generation feedstocks are expected to have much less of an adverse impact on soil quality and health than conventional corn-grain or soybean production. For example, the collection of MSW is likely to have little to no direct adverse affect on soil quality and health. The collection of forest residues and thinnings is also likely to have minimal direct adverse effects on soil quality and health, although some concerns have been raised regarding potential depletion of nutrients and compaction of soil during the removal of thinnings from forests if these activities are poorly managed (*45, 46*). It is currently unclear how potential upstream environmental burdens associated with MSW and forest residues may affect soil quality and health.

Compared to conventional corn-grain production, the collection of crop residues has the potential for greater detrimental impacts on soil quality and health. Specifically, the excessive removal (i.e., above tolerable limits) of crop residues such as corn stover can result in significant loss of source carbon (e.g., 800 pounds per ton harvested), reduced soil fertility, increased erosion, reduced microbial life, reduced water retention capacity, and increased weed growth relative to conventional corn-grain production (*10, 20, 38, 39, 45, 48, 51, 77, 83*). Although several studies have attempted to define sustainable removal rates for corn stover by controlling for erosion and water retention, current estimates of the amount of residue that should be left on the cornfield vary widely (i.e., 25−100% of the total available corn residue) and depend on crop, farming system, rotation, climate, soils, and other factors (*38, 39, 76, 83, 84*). Recent research also suggests that the amount of stover needed to maintain SOC is a greater constraint on sustainable removal rates than that needed to control soil moisture and erosion (*76*).

The production of most dedicated herbaceous energy crops is expected to have minimal negative impacts on soil quality and health for the reasons mentioned above (e.g., low chemical inputs, less intensive tillage) and could potentially improve local soil conditions depending on previous land use. Specifically, because of their deep root systems and year-round cover, perennial herbaceous energy crops have the potential to reduce soil erosion rates, sequester and enhance SOC, and increase soil fertility over time relative to annual corn-grain production (*9, 45, 50, 54, 56, 57, 60, 62*). For example, data from controlled switchgrass plots in the U.S. indicate approximately 30× lower soil erosion during the first year and more than 600× lower erosion by the second and third years of establishment compared to the historical production of annual crops (*56*). A study of established switchgrass stands and newly cultivated cropland also shows that SOC is approximately 10−20% greater for switchgrass than cropland sites at soil depths of 0−5 and 60−90 cm on a concentration basis (*60*). Additionally, measured SOC from annually harvested perennial grasses was not found not to differ significantly from an undisturbed native grassland, suggesting that perennial feedstocks will not adversely affect soil quality (*85*). Studies show that dedicated herbaceous energy crops may also improve soil conditions if grown on marginal land and when strategically placed as buffer strips to reduce soil erosion and chemical runoff associated with conventional cropping systems (*56*). Similarly, few chemical inputs are needed to produce most SRWC, and these crops can improve soil conditions because of their extensive fine root systems (*66*). For example, compared to conventional corn-grain production, SRWC can enhance SOC storage, reduce soil erosion and nonpoint source pollution, and improve soil quality on certain lands (*65, 66*).

Although there are perhaps greater uncertainties associated with the production of microalgae than other feedstocks, its cultivation in open ponds or closed reactors is not likely to have detrimental effects on the health and quality of the surrounding soil so long as the ponds are properly lined.

Water Use and Quality. Crop irrigation currently dominates U.S. water withdrawals, accounting for approximately 70% of total withdrawals (*86*−*88*). The percentage of existing cultivated cropland needing irrigation to supplement rainfall supply is regionally dependent and can range anywhere from 2−100% for corn and 0−30% for soybeans (with most irrigation occurring in western states) (*88*). However, the total amount of water used to irrigate these crop is locally and nationally significant (e.g., 11,830,000 acre-feet/yr and 4,409,000 acre-feet/yr for U.S. production of corn and soybeans, respectively) (*86, 88*). Additionally, although research suggests that there will be sufficient water resources to meet future biofuel feedstock production demands on a national level, water shortages could still be locally significant across the U.S. due to variations in climate and geology (*86, 88, 89*). Agricultural pesticide and fertilizer use associated with conventional crop production has also long been associated with significant adverse effects such as eutrophication of fresh and ocean waters caused by phosphorus and nitrogen runoff as well as elevated nitrate levels in groundwater associated with nitrate leaching (*86*). The hypoxic zone in the Gulf of Mexico is an example of how historical agricultural practices have contributed to significant water pollution impacts in the U.S. (*8, 90*).

Depending on allocation method, the production of most next-generation feedstocks is likely to have lower water demand and less adverse impacts on water quality compared to conventional corn-grain or soybean production. For example, the collection of MSW is not expected to directly consume water or to have negative water quality impacts (*42*). Similarly, the collection of forest residues and thinnings is projected to have minimal direct water demands relative to conventional corn-grain production, and some research suggests that reducing forest stand density by removing small diameter trees may decrease water loss from evapotranspiration and increase the amount of water stored in snowpack (*46*). Although water quality could be affected if the collection of forest residues and thinnings increases sediment loadings to streams (*46*), these impacts are likely to be offset by water quality benefits from a decrease in forest residue burnings and intensive wildfires, which can lead to soil erosion and sediment loadings. The harvesting of crop residues such as corn stover, is also expected to have lower total water demands than conventional corn-grain production which can be very water-intensive in certain regions. However, the replacement of nutrients removed with biomass may necessitate additional fertilizer input, which could exacerbate water quality impacts attributed to conventional corn-grain cropping systems (*48, 88*), and the removal of crop residues may increase soil erosion if not done at sustainable rates, thereby resulting in greater sediment runoff into waterways (*86*). In one LCA study, corn stover collected at a maximum allowable rate (based on controlling erosion) resulted in a 21% increase in eutrophication potential due to increased leaching of total nitrogen and phosphorus compared to traditional corn−soybean rotation production (*39*).

Overall, the production of dedicated herbaceous energy crops and SRWC is expected to have much lower total water demands than the production of corn-grain crops because of minimal irrigation requirements, although SRWC may have greater water demand than herbaceous energy crops (*64, 88, 91*). However, some research suggests that if these crops (like any crop) are grown on marginal land or as monocultures, substantial irrigation may be required to ensure their economic viability (*10, 92*). Other potential benefits are that certain dedicated herbaceous energy crops, such as switchgrass, may be much more water efficient and heat and drought tolerant than annual row crops such as corn (*50, 55*), and much research has focused on using municipal and/or industrial wastewater for the irrigation of these crops which could reduce local freshwater demand (*9*). Neither dedicated herbaceous energy crops nor SRWC are likely to have a significant adverse impact on water quality because of their minimal use of pesticides and fertilizers (*45, 86, 91*), and the production of these crops has the potential to improve water quality relative to conventional corn-grain production by reducing off-site transport of agricultural chemicals if planted as buffer zones between surface waterways and conventional crops (*45, 65, 91*). Dedicated herbaceous energy crop production is also likely to result in less nitrogen loading to surface and groundwater because of lower overall nitrogen requirements and more efficient nitrogen uptake and use by the crop as compared to corn (*57*). For example, data from controlled switchgrass plots in the U.S. indicated approximately 2−3× lower nitrate loss from soil during the second and third years of establishment, even when compared to no-till corn production (*56*).

Although the cultivation of microalgae requires significant volumes of makeup water due to evaporative losses from open ponds or cooling water demands for closed microalgae

TABLE 1. Comparison of Predicted Air Emissions, Water Use, and Water Quality Metrics From the Production of Next Generation Feedstocks Relative to Corn Using a LCA Model

		% change relative to corn production (per metric ton)		
		forest residues	switchgrass	corn stover
GHG emissions	carbon dioxide (CO_2)	−93	−90	−23
	dinitrogen monoxide (N_2O)	−99	−56	−23
	methane (CH_4)	−98	−83	−23
air pollutant emissions	carbon monoxide (CO)	−85	−89	−23
	lead (Pb)	−87	−88	−23
	nitrogen oxides (NO_x)	−75	−86	−23
	ozone (O_3)	−99	−89	−23
	particulates <2.5 mm ($PM_{2.5}$)	−94	−87	−23
	particulates <10 mm (PM_{10})	−90	−90	−23
	sulfur dioxide (SO_2)	−90	−92	−23
water use	groundwater	−100	−100	−23
water quality	atrazine loadings[a]	−100	−99	−23
	biological oxygen demand (BOD)	−85	−86	−23
	chemical oxygen demand (COD)	−87	−86	−23
	nitrate loadings	−100	−100	−23
	phosphorus loadings	−100	−100	−23

[a] Note that this pesticide is not currently registered for use on all feedstocks.

reactors (*29, 30, 67, 68*), microalgae production is expected to use substantially less fresh water compared to conventional soybean production because many species have been found to grow well in brackish or salt water (*9, 26, 29, 68, 70, 73*). The utilization of wastewater has also been proposed for microalgae cultivation, although this could cause contamination problems or complicate downstream processing (*69, 71−73*).

Biodiversity and Land-Use Changes. Increased production of biofuel feedstocks can require vast amounts of land. However, the extent to which large-scale land-use changes can negatively impact biodiversity and ecosystem services depends on the type of land that is used for feedstock production (e.g., degraded versus fertile land) and the method by which these feedstocks are grown (e.g., polycultures versus monocultures) (*9, 10*). Compared to meeting U.S. biofuels mandates with increased conventional corn-grain and soybean production, the production of certain next-generation feedstocks is expected to result in fewer land-use changes and biodiversity impacts, whereas others are likely to result in much greater effects on land-use or have the potential for larger biodiversity impacts.

Depending on allocation method, the use of waste products or residues as next-generation feedstocks can significantly reduce land requirements and ecological footprints compared to conventional corn-grain or soybean production. For example, the collection of MSW will have virtually no direct effect on land use or biodiversity, except perhaps a positive impact due to less material sent to landfills (*42*). The collection of forest residues and thinnings is also likely to result in minimal direct land-use and biodiversity changes because this feedstock is located on existing forest lands. Some research suggests that the removal of forest thinnings can even indirectly improve forest growth and ecosystem functioning due to less frequent and intensive wildfires (*43, 46*). However, detrimental impacts are anticipated if excessive amounts of forest thinnings are removed due to a variety of causes (e.g., machine damage to trees and tree scarring, changes in stand structure, habitat fragmentation and wildlife disturbances, introduction of non-native plants) (*10, 45, 46*). Similarly, harvesting of crop residues is likely to result in minimal land-use changes and effects on biodiversity because these materials are produced as co-products of existing agricultural systems on land already in production. However, pheasants and other wildlife that feed on grain left in corn fields may be adversely affected by excessive corn stover removal (*93*).

Compared to conventional corn-grain production which occurs on land already in use, dedicated herbaceous energy crops and SRWC are expected to result in greater land-use changes and potential positive or negative biodiversity impacts (*9, 10, 28, 66*). For example, several studies have found that the planting of dedicated herbaceous energy crops and SRWC can improve marginal land by promoting landscape restoration and diversity and enhancing species biodiversity and natural habitats (*51−53, 65, 66*). Certain dedicated herbaceous energy crops, such as switchgrass and miscanthus, can also provide wildlife cover and habitat for birds and other species (and harvesting can be timed to occur after birds have fledged) (*62, 93−95*), while prairie grasses can offer additional ecosystem services such as supporting pollinators (*9, 50, 51, 53*). Additional research suggests that some SRWC can enhance landscape diversity, provide good foraging and nesting habitat for a variety of bird species, and increase forest interior habitats or serve as corridors between forest patches if they are planted adjacent to natural forests (*65, 91*). However, adverse biodiversity effects could occur if dedicated herbaceous energy crops and SRWC are grown as monocultures or if high carbon lands (e.g., forests) are converted for their production (*9, 10, 28, 66*). Some research also suggests that certain next-generation crops could impact wildlife habitat and biodiversity preservation due to their spatial pattern of production (*51*). Additional concerns have been raised regarding the invasive potential of some of these crops, especially if they are genetically modified or not native to the region, although the utilization of native plants such as switchgrass and sterile cultivars of species such as miscanthus can alleviate concerns of invasiveness (*9, 28, 61, 62, 96*).

The cultivation of microalgae is estimated to potentially produce 10−100× more lipids per acre than plants such as soybeans, thereby requiring much less total land area (*29, 30, 67, 69, 70*). Open ponds or closed reactors can also be sited on marginal land, although there may be some constraints on the exact location of microalgae cultivation facilities because of the need for a continuous source of CO_2 and water (*26, 29, 73, 74*). It is currently unclear to what extent the production of microalgae, particularly in open ponds, might have an effect on local biodiversity.

Feedstock Production−LCA Modeling. Comparative analyses using LCA modeling generally confirm the findings reported above from the published literature (see Table 1). Specifically, the production of all three next-generation feedstocks modeled (forest residues, switchgrass, and corn stover) is estimated to fare better than corn-grain production

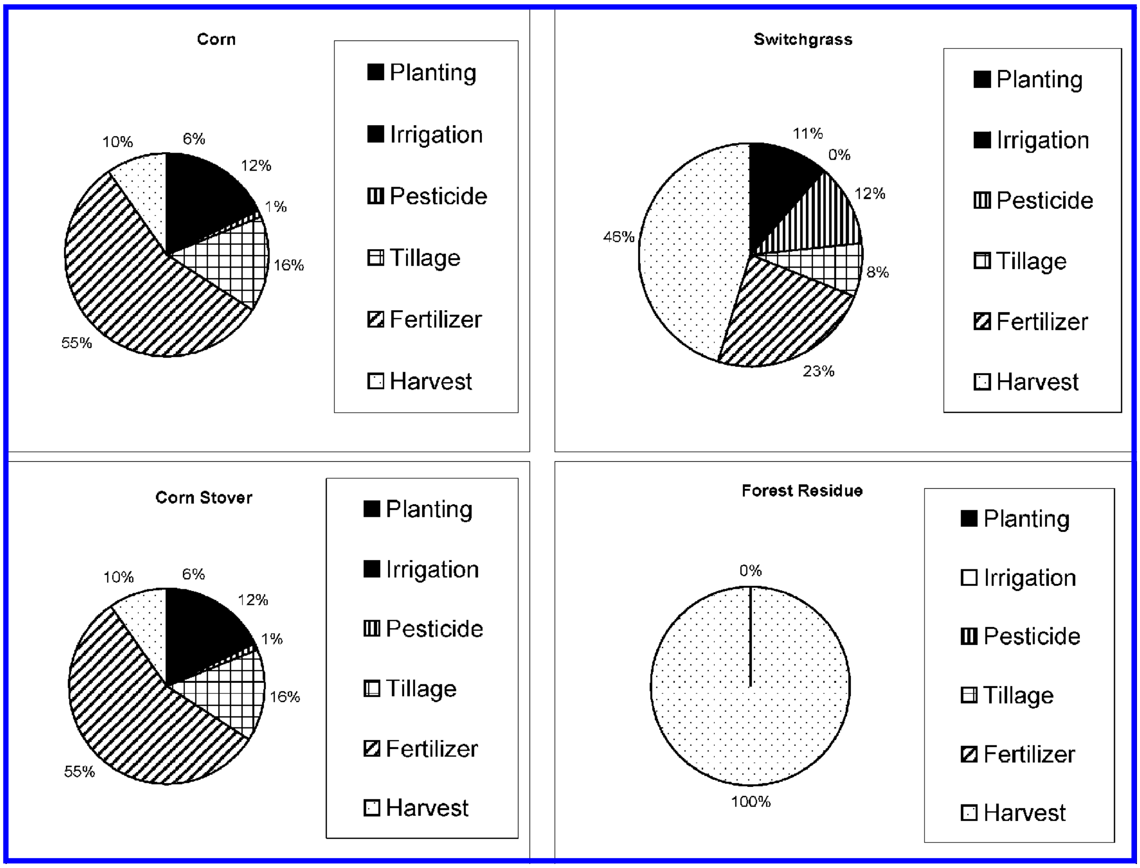

FIGURE 1. Source contribution for carbon dioxide (CO_2) emissions during feedstock production.

on all of the factors evaluated. Based on the modeling assumptions related to the allocation of environmental burdens for all three next-generation feedstocks (see Supporting Information), the production/collection of forest residues, switchgrass, and corn stover are estimated to result in approximately 93%, 89%, and 23% lower CO_2 emissions, respectively, than corn-grain production per ton of feedstock. However, the relative contribution of different sources to CO_2 emissions varies among feedstocks, with the production and application of fertilizers accounting for the greatest CO_2 emissions for corn grain and corn stover, whereas harvesting activities account for the greatest CO_2 emissions for switchgrass and forest residues (see Figure 1). During production processes, forest residues and switchgrass are also estimated to result in approximately 75−99% lower air pollutant emissions and a 100% reduction in water consumption and pesticide/fertilizer loadings to water on a per ton basis relative to corn-grain production. Corn stover is estimated to fare approximately 23% better than corn grain on a per ton basis on all factors. Note that our modeling does not assume any "credit" for avoided emissions, waste streams, or other environmental burdens (e.g., reduced air pollutant emissions from avoided burning of forest residues that are common current practices), so the actual reductions associated with production of next-generation feedstocks relative to corn-grain production may be much greater than the estimates provided here.

Ethanol Conversion—Review of Literature. Currently, the U.S. produces ethanol from corn grain by a dry grind or wet mill process (*6, 19, 22, 97, 98*). In a conventional ethanol biorefinery, corn starch is converted to sugars by cooking it at high temperature and using amylase enzymes to facilitate carbohydrate depolymerization to monomeric glucose. The glucose sugars are then fermented to produce ethanol and CO_2. Distillation separates the ethanol from the water and stillage downstream. The dominant proposed processes for conversion of next-generation cellulosic feedstocks to ethanol utilize biochemical (*99*) and thermochemical (*100*) platforms. The biochemical conversion platform uses yeast or bacteria, isolated enzymes, or strong acids to break down cellulose into fermentable sugars before operating in a manner similar to a corn-grain ethanol plant (*19, 21−23, 99, 101*). In contrast, the thermochemical conversion platform entails reacting feedstocks under conditions of limited oxygen and very high temperatures to create a synthesis gas (syngas), which is then converted to ethanol via a catalytic alcohol synthesis process after syngas cleaning and conditioning (*22, 23, 100*). It should be noted, however, that neither of the cellulosic conversion processes have been demonstrated on a commercial scale. Today's designs assume the existence of several plants using the same technology in order to eliminate the potential price spikes that might occur from "overengineering" a first-of-a-kind facility (*19, 99, 100*). Pioneer cellulosic ethanol biorefineries are therefore likely to be less efficient and produce greater emissions and waste streams than the optimized "n^{th}" plant designs.

GHG Emissions. Conventional ethanol biorefineries have become much more energy efficient over the last two decades, but these facilities are still dependent on fossil fuels (e.g., natural gas, coal) for heat and power (*6, 18, 19, 97, 98*). Cellulosic ethanol biorefineries are expected to rely on biomass instead of fossil fuels as an energy source by burning lignin residues generated during biochemical conversion processes and using a diverted portion of syngas produced during thermochemical processes (*19, 99, 100*). Cellulosic ethanol biorefineries are therefore expected to result in fewer total GHG emissions than conventional ethanol biorefineries because of their underlying source of heat and power. On the other hand, GHG emissions from conversion operations (e.g., scrubbing units, flue gas) are likely to be similar between conventional and cellulosic ethanol biorefineries (*102*). Additionally, it is currently unclear how cellulosic ethanol biorefineries will fare relative to conventional ethanol biorefineries in regards to GHG emissions associated with the production of various process inputs (e.g., ammonia, lime, sulfuric acid, enzymes). Note that CO_2 generated during conventional or cellulosic ethanol conversion can be collected and exported as a coproduct, thereby potentially mitigating or offsetting CO_2 emissions from these facilities (*6, 19*).

Total GHG emissions for cellulosic ethanol biorefineries are not expected to differ significantly between biochemical and thermochemical conversion platforms, but the proportionate contribution of different sources may vary. For biochemical conversion, the greatest CO_2 emissions are projected to occur from flue gas due to the burning of byproduct streams and combustion of lignin-rich residue in the boiler system (*38, 99*). Relatively small amounts of methane (CH_4) and N_2O are also predicted to be released from this source (*99*). Smaller quantities of CO_2 are estimated to be released during fermentation, in which CO_2 (which is a byproduct of the fermentation process) is collected and sent through a scrubber to separate the organics prior to venting (*38, 99*). For thermochemical conversion, the greatest CO_2 emissions are projected to occur from flue gas due to the combustion of char and the slipstream of syngas to provide heat to power the refinery (*100*). Relatively small amounts of CH_4 and N_2O are also predicted to be released from flue gas due to combustion processes (*100*). Smaller quantities of CO_2 are estimated to be released during gasification, in which CO_2 is vented to the atmosphere from the amine acid-gas scrubbing unit operations and during gas cleanup and conditioning after the removal of CO_2 from the cooled syngas (*100*). Although outside the scope of the current paper, these GHG emissions should be balanced against sequestration during the feedstock production stage (and added to emissions from all other stages) in a complete life-cycle accounting analysis.

Air Pollutant Emissions. Ethanol plants can emit significant amounts of VOCs, SO_x, NO_x, hazardous air pollutants, and particulate matter (*103*). The primary sources of air pollutant emissions from conventional corn-grain ethanol plants include the grain handling units, boilers, dried distillers grain with solubles (DDGS) dryers, fermentation, and distillation units (*103*). Although air pollution problems from the drying of distiller's grains have been associated with corn-grain ethanol plants in the past (*13*), most of these facilities have been retrofitted with thermal oxidizers to address these problems (*23*). However, cellulosic ethanol biorefineries are still expected to result in fewer total air pollutant emissions than conventional biorefineries due to the anticipated use of biomass instead of fossil fuels as an energy source. The only exception may be for SO_x emissions, which may be greater for some biochemical cellulosic ethanol biorefineries than conventional ethanol biorefineries (see discussion below) (*38*).

In general, biochemical and thermochemical cellulosic ethanol biorefineries are projected to produce similar emissions of air pollutants. An exception is SO_x emissions, which are likely to be greater during biochemical conversion processes if sulfuric acid is used as a pretreatment catalyst (i.e., residual sulfur can be present in the downstream lignin if the pretreatment mixture is not completely neutralized, thereby leading to SO_x formations during lignin burning). The sources of air pollutant emissions may also differ by conversion platform. For biochemical conversion, air pollutant emissions are expected to occur mainly from two sources in the process: scrubbed fermentation offgas and flue gas from the biomass fluidized bed combustor (*99*). Specifically, gaseous ethanol and VOCs are produced during fermentation, while SO_x, NO_x, and particulates are generated during the combustion of lignin residue (*99*). For thermochemical conversion, air pollutant emissions are expected to be produced in significant quantities only by the char and syngas combustor (*100*).

Water Use. Biorefineries require a significant amount of water to convert biomass to fuel (*86*). Water demands are primarily for process and cooling purposes, with some of the greatest consumptive losses from boiler blowdown and evaporation in the cooling tower (*19, 86, 100, 104*). Although the total amount of water consumed during ethanol conversion is projected to be small compared to that during feedstock production, biofuel conversion facilities can still stress local water supplies (*86*). Sources of fresh water used during ethanol conversion processes can vary depending on where a biorefinery is sited. For example, the primary source of fresh water for most existing corn-grain ethanol plants is from local groundwater aquifers, and some of these aquifers are not readily recharged (*100, 104*). Water sources for future cellulosic ethanol biorefineries are likely to be more diverse than for conventional ethanol biorefineries, perhaps comprising a mix of groundwater and surface water sources, due to their expected geographic diversity.

Overall, cellulosic ethanol biorefineries are expected to have water requirements similar to those of conventional ethanol biorefineries. Corn-grain ethanol plants have historically used more than 15 gal. of water per 1 gal. of ethanol produced, but newly built corn-grain ethanol dry mills use an average of 3.5 gal. of fresh water to produce 1 gal. of ethanol (*6, 18, 104, 105*). By comparison, biochemical cellulosic ethanol biorefineries are expected to use approximately 6 gal. of fresh water per 1 gal. of ethanol produced, whereas thermochemical cellulosic ethanol biorefineries are expected to use approximately 2 gal. of fresh water per 1 gal. of ethanol produced (*99, 100, 104, 105*). Biochemical conversion processes have greater projected water requirements than thermochemical conversion processes because the former platform is based on a design technology that was not optimized for water use, while the latter platform minimized water usage by using forced-air cooling in place of water in some locations (*99, 104, 106*). However, because a tar reforming catalyst is not yet commercially available for thermochemical conversion systems (*107*), pioneer thermochemical biorefineries will likely require greater volumes of process water to wash the tar than what is predicted by the optimized process design.

Wastewater. Wastewater at biofuel conversion facilities is mostly composed of unrecycled stillage with high organic content. A small amount of wastewater is also periodically generated from salt buildup in cooling towers and boilers from evaporation and scaling and brine effluent from water purification (*86*). Because water containing organic compounds is not allowed to be discharged into rivers, wastewater produced at biofuel conversion facilities must be treated either onsite or off-site at a local wastewater treatment facility (*18*). Although corn-grain ethanol plants have produced large amounts of wastewater in the past (*13*), newer ones are typically designed to have a high degree of water recycling and "zero wastewater discharge" (i.e., up to about 10,000 gallons per year) (*18, 19, 86, 100*).

Both biochemical and thermochemical cellulosic ethanol biorefineries are also designed for zero wastewater discharge and are expected to have virtually all process water recycled through a series of onsite separation, evaporation, and anaerobic and aerobic wastewater treatment steps (*99, 100, 104*). However, scrubbing water generated during thermochemical conversion processes may require off-site wastewater treatment to economically treat the tars and other organic contaminants scrubbed from the syngas.

Solid Waste. Conventional ethanol biorefineries generate very little solid waste. In contrast, cellulosic ethanol biorefineries are expected to generate solid waste from several sources, including the boiler and conditioning tanks. The

TABLE 2. Predicted Air Emissions, Water Use, and Waste Streams From Ethanol Conversion Based on Next-Generation Feedstocks and Cellulosic Conversion Technologies Using a Process Engineering Model

		model estimates (kg per L of ethanol)[c]					
		forest residues		switchgrass		corn stover	
		biochemical	thermochemical	biochemical	thermochemical	biochemical	thermochemical
GHG Emissions	carbon dioxide (CO_2)[a]	0.75	0.85	0.75	0.85	0.75	0.82
	carbon dioxide (CO_2)[b]	2.74	3.50	2.89	3.68	2.11	3.63
	methane (CH_4)[b]	0.00003	0.00	0.0001	0.00	0.0001	0.00
air pollutant emissions	carbon monoxide (CO)[b]	0.002	0.00	0.003	0.00	0.002	0.00
	nitrogen oxides (NO_x)[b]	0.002	0.005	0.003	0.027	0.002	0.033
	sulfur dioxide (SO_2)[b]	0.003	0.0003	0.004	0.003	0.003	0.002
water use	fresh (make-up)	7.20	2.56	8.61	2.17	6.16	2.67
waste water	treated (off-site)	0.00	0.03	0.00	0.03	0.00	0.03
solid waste	ash/sand	0.03	0.03	0.16	0.37	0.14	0.05
	gypsum waste	0.23	0.00	0.28	0.00	0.24	0.00
	sulfur	0.00	0.0002	0.00	0.002	0.00	0.001

[a] Emissions from scrubbed CO_2 vent. [b] Emissions from flue gas. [c] kg per ton (dry) assuming 2000 dry metric tonnes per day and 15% moisture content of feedstock.

composition of the solid waste streams is also expected to differ between biochemical and thermochemical conversion platforms due to different chemical inputs and production processes. For example, biochemical conversion processes are expected to generate large amounts of gypsum if lime is used as a conditioning agent (*99*). Research is currently underway using ammonium hydroxide as an alternative hydrolysate conditioning agent, which will eliminate this solid waste stream (*106*). Thermochemical conversion processes are expected to generate small amounts of elemental sulfur from the scrubbed syngas (*100*). Both biochemical and thermochemical conversion processes are expected to generate varying amounts of boiler ash depending on the ash content of the cellulosic feedstock.

Ethanol Conversion—Process Engineering Modeling. Comparative analyses using a process engineering model generally confirm findings reported in the published literature (see Table 2). For example, both conversion platforms are predicted to have similar estimated CO_2 and air pollutant emissions from two primary streams (CO_2 vent and flue gas). However, the biochemical conversion platform is estimated to produce approximately 2−10× greater SO_x emissions than the thermochemical conversion platform, while the thermochemical conversion platform is estimated to produce approximately 2 to 17× greater NO_x emissions than the biochemical conversion platform. Also, as expected, the biochemical conversion platform (which was not optimized for water use) is estimated to use 2−4× more water than the thermochemical conversion platform. Only the thermochemical conversion platform is predicted to produce wastewater requiring off-site treatment, while the solid waste streams are projected to differ by conversion platform (i.e., large amounts of gypsum are generated from the biochemical conversion platform, while small amounts of sulfur are generated from the thermochemical conversion platform). Note that these comparisons assume a dilute acid pretreatment process to break down hemicellulose in the biochemical conversion platform. Although there are many other alternative pretreatment technologies in development, preliminary modeling by the National Renewable Energy Laboratory (NREL) show little difference in overall emissions or effluent streams if hot water or ammonia-based processes are used instead (the use of lime has not yet been adequately studied).

Discussion

The current paper summarizes the state-of-knowledge of what is known or anticipated about environmental and sustainability factors associated with next-generation biofuels relative to conventional biofuels during feedstock production and conversion processes in the U.S. Based on our review of the available literature and modeling analyses, we find that next-generation biofuels are expected to fare better on most of these factors compared to conventional biofuels, but the magnitude of these differences may vary significantly and will depend on many factors (e.g., prior land use, management practices). Although environmental releases can also occur during other stages of the biofuels supply chain (i.e., feedstock logistics, fuel distribution, and vehicle operation), GHG and air pollutant emissions are projected to be insignificant during these stages when compared to feedstock production and conversion steps, except for air pollutant emissions from vehicle operations (*27, 38, 108*−*112*). However, vehicle operation-related emissions would not vary substantially between conventional and next-generation biofuels because the properties of the biofuel (e.g., ethanol) will remain nearly the same regardless of underlying feedstock. Despite the generally positive expectations associated with next-generation biofuels, there is significant uncertainty regarding how well these biofuels will fare on different environmental and sustainability factors when produced on a commercial scale. To fill important data gaps and ensure that next-generation biofuels are produced in the U.S. in a sustainable manner, additional research is needed in the following five general areas:

(1) Studies utilizing medium- and large-scale, multiacre field trials and modeling efforts that reflect geographical differences as well as alternative feedstock production and management practices. These studies should evaluate the influence of site-specific conditions (e.g., climate, rainfall, soil type, proximity to water sources) on soil and water quality and water demands for different next-generation feedstocks. These studies should also examine the extent to which different types of management practices (e.g., no-till farming, advanced fertilizer application technologies, cover crops and riparian plantings, crops grown as polycultures) can influence stored carbon levels and improve water quality and ecosystem services. Additional research is needed to assess the potential environmental effects of new feedstock varieties or cultivars that are genetically modified for specific traits (e.g., stress and drought resistance, water and nutrient use efficiency, pest control). Moreover, future research in this area should target a broad spectrum of potential next-generation feedstocks, rather than a selected subset, with a particular focus on those that have received relatively little research attention

but which may have few negative environmental implications (e.g., MSW, microalgae, native prairie grasses).

(2) Research on the potential environmental effects of major land-use changes in the U.S. associated with the production of next-generation biofuels. In particular, this research should attempt to better characterize how the use of different types of land for feedstock production may impact GHG emissions, soil carbon levels, water quality and demand, biodiversity losses, and land use function. For example, standardized approaches and analytical tools are needed to better quantify GHG emissions from direct and indirect land use changes due to the production of different feedstocks. More research is needed to determine whether using marginal or un-utilized arable land to produce different feedstocks will result in significant biodiversity losses or require sizable inputs of nutrients, pesticides, and water. Ideally, research on potential land-use changes should emphasize a systems approach that focuses on ecosystems services and considers environmental effects on several spatial and temporal scales (*10, 34, 45*).

(3) Research to optimize the efficiencies of next-generation conversion technologies. In particular, this research should focus on alternative ways to reduce energy consumption and transfer heat at cellulosic ethanol biorefineries, which can lead to fewer emissions, lower water consumption, and reduced waste streams. For the biochemical conversion platform, ongoing research should continue to explore opportunities for optimal water use and advanced pretreatment and consolidated processing steps (*21, 22, 99, 106*) that considers potential environmental releases associated with different processes. For the thermochemical conversion platform, additional research is needed to commercialize catalyst technologies for tar reforming and mixed alcohol synthesis (*100, 107*). More research is also needed to assess the potential benefits of hybrid techniques that integrate biochemical and thermochemical conversion technologies (*28, 100, 113*). Future research in this area should evaluate other advanced conversion technologies, such as pyrolysis, that can be used to produce a variety of renewable and advanced fuels (e.g., green gasoline, green diesel, jet fuel) and which can use existing infrastructure (*114, 115*).

(4) Research on the ultimate environmental and health impacts of biofuels across all life-cycle stages and standardized approaches for assessing sustainable biofuels production. This research should focus on modeling and analytical tools that move beyond initial *inventory* assessments that track environmental flows and releases, to more quantitative *impact* assessments that characterize direct and indirect environmental and health outcomes due to these releases (*57, 116*). As part of this effort, more research is needed to standardize systems boundaries and allocation methods for quantifying life-cycle environmental burdens between products and coproducts. A related research topic should be the development of universally accepted metrics for evaluating and comparing environmental and health impacts associated with biofuels across multiple scales (*34, 45, 117*). Note that efforts are currently underway in the U.S. and abroad to develop science-based criteria and indicators for sustainable biofuels production, including a white paper being prepared by the Sustainability Interagency Working Group of the Biomass R&D Board. International governmental and non-governmental organizations, such as the Global Bioenergy Partnership and Roundtable on Sustainable Biofuels (*118*), are also developing standards, benchmarks, and principles and criteria for assessing sustainable biofuels production. However, these national and international organizations will need to work together to develop globally agreed upon sustainability metrics, especially if they are to be used for certification schemes or mandatory trade guidelines for biofuels. Data and modeling limitations also hinder our ability to identify, measure, and evaluate many environmental indicators and research will be necessary to address these shortcomings and ensure the most appropriate benchmarks and metrics are adopted (*117*).

(5) Research on environmental and sustainability trade-offs associated with the production of different biofuels and the influence of different technology and management choices using new decision-support modeling tools. This research area should focus on the development of analytical tools that are capable of identifying, quantifying, and weighing uncertainties and potential trade-offs (e.g., minimizing GHG emissions vs increasing aqueous effluent) associated with different biofuels production decisions. This research will likely entail utilizing geographic information system (GIS) information and linking process-oriented models and sector models to develop a consistent framework that explicitly considers such trade-offs and other unintended consequences (*10, 45*). These tools are necessary to ensure that the most optimal technology, management, and policy decisions are made regarding biofuel production, including which next-generation feedstocks should be produced in a specific location, what feedstock management practices should be used, and where cellulosic biorefineries should be sited.

Acknowledgments

This work was performed while P.R.W. was an employee at the U.S. Environmental Protection Agency (EPA), Office of Research and Development, on detail to the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. All other authors affiliated with DOE's National Renewable Energy Laboratory (NREL) received financial support under DOE contract DE-AC36-08GO28308. Any views or opinions expressed herein are those of the authors only and do not necessarily reflect those of the EPA, DOE, or NREL. We thank Zia Haq, Alison Goss Eng, John Ferrell, and Jacques Beaudry-Losique with DOE's Office of Biomass Program for their review of the scope and content of this manuscript. We also thank Alan Hecht and George Gray (EPA), Dale Gardner (NREL), and Virginia Dale and Keith Kline (ORNL) for their helpful comments on this manuscript and insight regarding sustainable biofuels production. Additionally, we acknowledge Kelly Tiller (University of Tennessee), William Davis and John Cuzens (BlueFire Ethanol), and Mitch Mandich and Bud Klepper (RangeFuels) for providing site tours and information on biofuels produced from switchgrass, MSW, and forest residues, respectively.

Supporting Information Available

Additional information regarding the modeling tools, data sources, and assumptions used to estimate potential environmental emissions, waste streams, and water consumption associated with feedstock production and ethanol conversion. This information is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Pacala, S.; Socolow, R. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* **2004**, *305*, 968–972.
(2) Biomass Research and Development Act of 2000. Public Law 106-224.
(3) Energy Policy Act of 2005. Public Law 109-58.
(4) Energy and Independence Security Act of 2007. Public Law 110-140.
(5) Biomass Research and Development Board. *National Biofuels Action Plan*; BR&Di: Washington, DC, 2008; http://www1.eere.energy.gov/biomass/pdfs/nbap.pdf.
(6) Wu, M. *Analysis of the Efficiency of the U.S. Ethanol Industry 2007*; Argonne National Laboratory: Argonne, IL, 2008.

(7) Biomass Research and Development Board. *Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications and the Role of Research*; BR&Di: Washington, DC, 2008. Available at http://www.brdisolutions.com/Site%20Docs/Increasing%20Feedstock_revised.pdf.

(8) Donner, S. D.; Kucharik, C. J. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105*, 4513–4518.

(9) Groom, M. J.; Gray, E. M.; Townsend, P. A. Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conserv. Biol.* **2008**, *22*, 602–609.

(10) Robertson, G. P.; Dale, V. H.; Doering, O. C.; Hamburg, S. P.; Melillo, J. M.; Wander, M. M.; Parton, W. J.; Adler, P. R.; Barney, J. N.; Cruse, R. M.; Duke, C. S.; Fearnside, P. M.; Follett, R. F.; Gibbs, H. K.; Goldemberg, J.; Mladenoff, D. J.; Ojima, D.; Palmer, M. W.; Sharpley, A.; Wallace, L.; Weathers, K. C.; Wiens, J. A.; Wilhelm, W. W. Sustainable biofuels redux. *Science* **2008**, *322*, 49–50.

(11) Engelhaupt, E. Biofueling water problems. *Environ. Sci. Technol.* **2007**, *41*, 7593–7595.

(12) Hill, J. Environmental costs and benefits of transportation biofuel production from food-and lignocellulose-based energy crops. A review. *Agron. Sustain. Dev.* **2007**, *27*, 1–12.

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

(14) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1237.

(15) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Fengxia, D.; Elobeid, A.; Gabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319*, 1238–1240.

(16) Kline, K. L.; Dale, V. H. Biofuels: effects on land and fire. *Science* **2008**, *321*, 199.

(17) Morris, D. *Ethanol and Land Use Changes*; ILSR: Washington, DC, 2008. Available at http://www.newrules.org/sites/newrules.org/files/images/ethanol-and-land-use.pdf.

(18) Shapouri, H.; Gallagher, P. *USDA's 2002 Ethanol Cost-of-Production Survey*; USDA: Washington, DC, 2005.

(19) McAloon, A.; Taylor, F.; Yee, W.; Ibsen, K.; Wooley, R. *Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks*; NREL: Golden, CO, 2000.

(20) Kline, K. L.; Oladosu, G. A.; Wolfe, A. K.; Perlack, R. D.; Dale, V. H.; McMahon, M. *Biofuel Feedstock Assessment for Selected Countries: To Support the DOE Study of Worldwide Potential to Produce Biofuels with a Focus on U.S. Imports*; ORNL: Oak Ridge, TN, 2008.

(21) U.S. Department of Energy. *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda. A Research Roadmap Resulting from the Biomass to Biofuels Workshop*; DOE: Washington, DC, 2006.

(22) U.S. Environmental Protection Agency. *Biomass Conversion: Emerging Technologies, Feedstocks, and Products*; EPA: Washington, DC, 2007.

(23) Granada, C. B.; Zhu, L.; Holtzapple, M. T. Sustainable liquid biofuels and their environmental impact. *Environ. Prog.* **2007**, *26*, 233–250.

(24) Perlack, R. D.; Wright, L. L.; Turhollow, A. F.; Graham, R. L.; Stokes, B. J.; Erbach, D. C. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply*; ORNL: Oak Ridge, TN, 2005.

(25) Kim, S.; Dale, B. E. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy* **2004**, *26*, 361–375.

(26) Holzman, D. C. The carbon footprint of biofuels: can we shrink it down to size in time. *Environ. Health Perspect.* **2008**, *116*, A246–A252.

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

(28) Sims, R. H.; Hastings, A.; Schlamadinger, B.; Taylor, G.; Smith, P. Energy crops: current status and future prospects. *Global Change Biol.* **2006**, *12*, 2054–2076.

(29) Campbell, M. M. Biodiesel: algae as a renewable source for liquid fuel. *Guelph Eng. J.* **2008**, *1*, 2–7.

(30) Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306.

(31) Kumar, N.; Sharma, P. B. *Jatropha curcus* - a sustainable source for production of biodiesel. *J. Sci. Ind. Res.* **2005**, *64*, 883–889.

(32) Van Gerpen, J.; Gray, A.; Shanks, B. H. *Convergence of Agriculture and Energy: III. Considerations in Biodiesel Production*; CAST: Ames, IA, 2008.

(33) Kim, H.; Kim, S.; Dale, B. E. Biofuels, land use change, and greenhouse gas emissions: some unexplored variables. *Environ. Sci. Technol.* **2009**, *43*, 961–967.

(34) Dale, V. H.; Wright, L. L.; Kline, K. L.; Perlack, R. D.; Graham, R. L.; Downing, M. E. Interactions between bioenergy feedstock choices, landscape dynamics, and land use. *Ecol. Applications* 2009,In Review.

(35) Kodera, K. Analysis of Allocation Methods of Bioethanol LCA; Vrije Universiteit, Amsterdam, 2007. Available at http://www.leidenuniv.nl/cml/ssp/students/keiji_kodera/analysis_allocation_methods_bioethanol.pdf.

(36) Kim, S.; Dale, B. E. Allocation Procedure in Ethanol Production System from Corn Grain. *Int. J. LCA* **2002**, *7*, 237–243.

(37) Kalogo, Y.; Habibi, S.; Maclean, H. L.; Joshi, S. V. Environmental implications of municipal solid waste-derived ethanol. *Environ. Sci. Technol.* **2007**, *41*, 35–41.

(38) Sheehan, J.; Aden, A.; Paustian, K.; Killian, K.; Brenner, J.; Walsh, M.; Nelson, R. Energy and environmental aspects of using corn stover for fuel ethanol. *J. Indust. Ecol.* **2004**, *7*, 117–146.

(39) Powers, S. E. *Quantifying Cradle-to-Farm Gate Life-Cycle Impacts Associated with Fertilizer Used for Corn, Soybean, and Stover Production*; NREL: Golden, CO, 2005.

(40) Scharlemann, J. P. W.; Laurance, W. F. How green are biofuels? *Science* **2008**, *319*, 43–44.

(41) Conant, R. T.; Paustian, K.; Del Grosso, S. J.; Parton, W. J. Nitrogen pools and fluxes in grassland soils sequestering carbon. *Nutr. Cycling Agroecosyst.* **2005**, *71*, 239–248.

(42) Li, A.; Khraisheh, M. Municipal solid waste used as bioethanol sources and its related environmental impacts. *Int. J. Soil, Sed., Water* **2008**, *1*, 1–5.

(43) Leinonen, A. *Harvesting Technology of Forest Residues for Fuel in the USA and Finland*; VTT: Helsinki, Finland, 2004. Available at http://www.vtt.fi/inf/pdf/tiedotteet/2004/T2229.pdf.

(44) Hollenstein, K.; Graham, R. L.; Shepperd, W. D. Biomass flow in the western forests: simulating the effects of fuel reduction and presettlement restoration treatments. *J. Forestry* **2001**, *99*, 12–19.

(45) Graham, R. L. Forecasting the magnitude of sustainable biofeedstock supplies: the challenges and the rewards. *Biofuels, Bioprod. Biorefin.* **2007**, *1*, 255–263.

(46) Graham, R. L.; Huff, D. D.; Kaufmann, M. R.; Shepperd, W. D.; Sheehan, J. Bioenergy and watershed restoration in the mountainous regions of the west: what are the environmental/community issues? *BioEnergy/98: Expanding BioEnergy Partnerships* **1998**, 1262–1271.

(47) National Renewable Energy Laboratory. *U.S. Life-Cycle Inventory Database*; NREL: Golden, CO, 2009. Available at http://www.nrel.gov/lci/.

(48) Lal, R. Soil and environmental implications of using crop residues as biofuel feedstock. *Int. Sugar J.* **2006**, *108*, 161–167.

(49) Edwards, W. *Estimating a Value for Corn Stover*. Iowa State University: Ames, IA, 2007.

(50) Wright, L. *Historical Perspective on How and Why Switchgrass was Selected as a "Model" High-Potential Energy Crop*; ORNL: Oak Ridge, TN, 2007.

(51) Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, 11206–11210.

(52) Junginger, M.; Faigg, A.; Rosillo-Calle, F.; Wood, J. The growing role of biofuels - opportunities, challenges, and pitfalls. *Int. Sugar. J.* **2006**, *108*, 618–629.

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

(54) McLaughlin, S. B.; Kszos, L. A. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass Bioenergy* **2005**, *28*, 515–535.

(55) Parrish, D. J.; Fike, J. H. The biology and agronomy of switchgrass for biofuels. *Crit. Rev. Plant Sci.* **2005**, *24*, 423–459.

(56) McLaughlin, S. B.; De La Torre Ugarte, D. G.; Garten, C. T., Jr.; Lynd, L. R.; Sanderson, M. A.; Tolbert, V. R.; Wolf, D. D. High-value renewable energy from prairie grasses. *Environ. Sci. Technol.* **2002**, *36*, 2122–2129.

(57) McLaughlin, S. B.; Walsh, M. E. Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass Bioenergy* **1998**, *14*, 317–324.

(58) Hill, J.; Polasky, S.; Nelson, E.; Tilman, D.; Huo, H.; Ludwig, L.; Neumann, J.; Zheng, H.; Bonta, D. Climate change and health costs of air emissions from biofuels and gasoline. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106*, 2077–2082.
(59) Perrin, R.; Vogel, K.; Schmer, M.; Mitchell, R. Farm-scale production cost of switchgrass for biomass. *Bioenergy Res.* **2008**, *1*, 91–97.
(60) Liebig, M. A.; Johnson, H. A.; Hanson, J. D.; Frank, A. B. Soil carbon under switchgrass stands and cultivated cropland. *Biomass Bioenergy* **2005**, *28*, 347–354.
(61) Heaton, E. A.; Dohleman, F. G.; Long, S. P. Meeting US biofuel goals with less land: the potential of Miscanthus. *Global Change Biol.* **2008**, *14*, 2000–2014.
(62) Lewandowski, I.; Scurlock, J. M. O.; Lindvall, E.; Christou, M. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass Bioenergy* **2003**, *25*, 335–361.
(63) U.S. Department of Agriculture. *NASS Agricultural Chemical Usage 2005 Field Crops Summary*; USDA: Washington, DC, 2006. Available at http://www.nass.usda.gov.
(64) Sokhansanj, S.; Mani, S.; Turhollow, A.; Kumar, A.; Bransby, D.; Lynd, L.; Laser, M. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.) - current technology and envisioning a mature technology. *Biofuels, Bioprod. Biorefin.* **2009**, *3*, 124–141.
(65) Volk, T. A.; Abrahamson, L. P.; Nowalk, C. A.; Smart, L. B.; Tharakan, P. J.; White, E. H. The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. *Biomass Bioenergy* **2006**, *30*, 715–727.
(66) Keoleian, G. A.; Volk, T. A. Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. *Crit. Rev. Plant Sci.* **2005**, *24*, 385–406.
(67) Darzins, A. *Algal-Derived Oil Feedstock R&D at NREL: Beyond the Aquatic Species Program*; NREL: Golden, CO, 2008.
(68) Darzins, A. Personal communication; NREL: Golden, CO, 2008.
(69) Dismukes, G. C.; Carrieri, D.; Bennette, N.; Ananyev, G. M.; Posewitz, M. C. Aquatic phototrophs: efficient alternatives to land-based crops for biofuels. *Curr. Opin. Biotechnol.* **2008**, *19*, 235–240.
(70) Sheehan, J. H.; Dunahay, T.; Benemann, J.; Roessler, P. *A Look Back at the U.S. Department of Energy's Aquatic Species Program - Biodiesel from Algae: Close-Out Report*; NREL: Golden, CO, 1998.
(71) Wang, B.; Li, Y.; Wu, N.; Lan, C. Q. CO_2 bio-mitigation using microalgae. *Appl. Microbiol. Biotechnol.* **2008**, *79*, 707–718.
(72) Patil, V.; Tran, K. Q.; Giselrod, H. R. Towards sustainable production of biofuels from microalgaev. *Int. J. Mol. Sci.* **2008**, *9*, 1188–1195.
(73) Hu, Q.; Sommerfeld, M.; Jarvis, E.; Ghiradi, M.; Posewitz, M.; Seibert, M.; Darzins, A. Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *Plant J.* **2008**, *54*, 621–639.
(74) Li, Q.; Du, W.; Liu, D. Perspectives of microbial oils for biodiesel production. *Appl. Microbiol. Biotechnol.* **2008**, *80*, 749–756.
(75) Reijnders, L. Do biofuels from microalgae beat biofuels from terrestrial plant? *Trends Biotechnol.* **2008**, *26*, 349–350.
(76) Wilhelm, W. W.; Johnson, J. M. F.; Karlen, D. L.; Lightle, D. T. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy J.* **2007**, *99*, 1665–1667.
(77) Johnson, J. M. F.; Allmaras, R. R.; Reicosky, D. C. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agron. J.* **2006**, *98*, 622–636.
(78) Andress, D. *Soil Carbon Changes for Bioenergy Crops*; DOE: Washington, DC, 2002.
(79) Pimentel, D.; Harvey, C.; Resosudarmo, P.; Sinclair, K.; Kurtz, D.; McNair, M.; Crist, S.; Sphritz, L.; Fitton, L.; Saffouri, R.; Blair, R. Environmental and economic costs of soil erosion and conservation benefits. *Science* **1995**, *276*, 1117–1123.
(80) Blanco-Canqui, H.; Lal, R. No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Sci. Soc. Am. J.* **2008**, *72*, 693–701.
(81) Baker, J. M.; Ochsner, T. E.; Ventera, R. T.; Griffis, T. J. Tillage and soil carbon sequestration - what do we really know? *Agric. Ecosyt. Environ.* **2007**, *118*, 1–5.
(82) Dolan, M. S.; Clapp, C. E.; Allmaras, R. R.; Baker, J. M.; Molina, J. A. E. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil Till. Res.* **2006**, *89*, 221–231.
(83) Graham, R. L.; Nelson, R.; Sheehan, J.; Perlack, R. D.; Wright, L. L. Current and potential U.S. corn stover supplies. *Agron. J.* **2007**, *99*, 1–11.
(84) Varvel, G. E.; Vogel, K. P.; Mitchell, R. B.; Follett, R. F.; Kimble, J. M. Comparison of corn and switchgrass on marginal soils for bioenergy. *Biomass Bioenergy* **2008**, *32*, 18–21.
(85) Mikhailovaa, E. A.; Bryanta, R. B.; Vassenevb, I. I.; Schwagerc, S. J.; Posta, C. J. Cultivation effects on soil carbon and nitrogen contents at depth in the Russian chernozem. *Soil Sci. Soc. Am. J.* **2000**, *64*, 738–745.
(86) National Research Council. *Water Implications of Biofuels Production in the U.S*; The National Academies Press: Washington, DC, 2008.
(87) Berndes, G. Bioenergy and water - the implications of large-scale bioenergy production for water use and supply. *Global Environ. Change* **2002**, *12*, 253–271.
(88) Pellegrino, J.; Antes, M.; Zotter, B.; Andres, H.; Scher, C. *Water Impacts from Increased Biofuels Production: An Analysis of Water Issues Based on Future Feedstock Production Scenarios*; NREL: Golden, CO, 2007.
(89) King, C.; Webber, M. E. Water intensity of transportation. *Environ. Sci. Technol.* **2008**, *42*, 7866–7872.
(90) U.S. Environmental Protection Agency. *Hypoxia in the Northern Gulf of Mexico*; EPA: Washington, DC, 2009. Available at http://epa.gov/msbasin/pdf/sab_report_2007.pdf.
(91) Graham, R. L.; Downing, M.; Walsh, M. E. A framework to assess regional environmental impacts of dedicated energy crop production. *Environ. Manage.* **1996**, *20*, 475–485.
(92) Fingerman, K.; Kammen, D.; O'Hare, M. *Integrating Water Sustainability into the Low Carbon Fuel Standard*; University of California: Berkeley, CA, 2008. Available at http://rael.berkeley.edu/files/Fingerman_WaterSust.pdf.
(93) Murray, L. D.; Best, L. B.; Jacobsen, T. J.; Braster, M. L. Potential effects on grassland birds of converting marginal cropland to switchgrass biomass production. *Biomass Bioenergy* **2003**, *25*, 167–175.
(94) Semere, T.; Slater, F. M. Ground flora, small mammal and bird species diversity in miscanthus (*Miscanthus* × *giganteus*) and reed canaray-grass (*Phalaris arundinacea*) fields. *Biomass Bioenergy* **2007**, *31*, 20–29.
(95) Roth, A. M.; Sample, D. W.; Ribic, C. A.; Paine, L.; Undersander, D. J.; Bartelt, G. A. Grassland bird response to harvesting switchgrass as a biomass energy crop. *Biomass Bioenergy* **2005**, *28*, 490–498.
(96) DiTomaso, J. M.; Barney, J. N.; Fox, A. M. *Biofuel Feedstocks: The Risk of Future Invasions*; CAST: Ames, IA, 2007.
(97) Renewable Fuels Association. *How Ethanol Is Made*; RFA: Washington, DC, 2009. Available at http://www.ethanolrfa.org/resource/made/.
(98) Eggeman, T.; Verser, D. The importance of utility systems in today's biorefineries and a vision for tomorrow. *Appl. Biochem. Biotechnol.* **2006**, *130*, 361–381.
(99) Aden, A.; Ruth, M.; Ibsen, K.; Jechura, J.; Neeves, K.; Sheehan, J.; Wallace, B.; Montague, L.; Slayton, A.; Lukas, J. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*; NREL: Golden, CO, 2002.
(100) Philips, S.; Aden, A.; Jechura, J.; Dayton, D.; Eggeman, T. *Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass*; NREL: Golden, CO, 2007.
(101) Gray, K. A. Cellulosic ethanol - state of the technology. *Int. Sugar J.* **2007**, *109*, 146–151.
(102) Foust, T. D.; Aden, A.; Dutta, A.; Phillips, S. A rigorous comparison of biofuels conversion processes for near and long term scenarios. *Cellulose* 2009,In Review.
(103) U.S. Environmental Protection Agency. *Environmental Laws Applicable to Construction and Operation of Ethanol Plants*; EPA: Kansas City, KS, 2007. Available at http://www.epa.gov/Region7/priorities/agriculture/ethanol_plants_manual.pdf.
(104) Aden, A. Water usage for current and future ethanol production. *Southwest Hydrol.* **2007**, (Sept./Oct.), 22–23.
(105) Wu, M.; Mintz, M.; Wang, M.; Arora, S. *Consumptive Water Use in the Production of Bioethanol and Petroleum Gasoline*; ANL: Argonne, IL, 2008.
(106) Aden, A. *Biochemical Production of Ethanol from Corn Stover: 2007 State of Technology Model*; NREL: Golden, CO, 2008.
(107) Carpenter, D. L.; Deutch, S. P.; French, R. J. Quantitative measurement of biomass gasifier tars using a molecular-beam mass spectrometer: Comparison with traditional impinger sampling. *Energy Fuels* **2007**, *21*, 3036–3043.
(108) Wang, M. *Well-to-Wheels Energy and Greenhouse Gas Emission Results of Fuel Ethanol*; USDA: Washington, DC, 2008.

(109) Wu, M.; Wu, Y.; Wang, M. Energy and emission benefits of alternative transportation liquid fuels derived from switchgrass: a fuel life cycle assessment. *Biotechnol. Prog.* **2006**, *22*, 1012–1024 .

(110) Dias de Oliviera, M. E.; Vaughan, V. B.; Rykiel, E. J. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *BioSci.* **2005**, *55*, 593–602.

(111) Niven, R. K. Ethanol in gasoline: environmental impacts and sustainability review article. *Renewable Sustainable Energy Rev.* **2005**, *9*, 535–555.

(112) Spatari, S.; Zhang, Y.; MacLean, H. L. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Technol.* **2005**, *39*, 9750–9758.

(113) Schmidt, L. D.; Daunhauer, P. J. Hybrid routes to biofuels. *Nature* **2007**, *447*, 914–915.

(114) Hsu, D.; Bain, R. L.; Elliott, D. C.; Butner, S. Life cycle assessment of the pyrolysis of corn stover into hydrotreated gasoline and diesel; presentation at AIChe annual meeting, Nov. 19, 2008.

(115) Kalnes, T.; Marker, T.; Shonnard, D.; Koers, K. *Life Cycle Assessments for Green Diesel Production*; The World Congress on Industrial Biotechnology & Bioprocessing, 2008.

(116) Zah, R.; Böni, H.; Gauch, M.; Hischler, R.; Lehmann, M.; Wäger, P. *Life Cycle Assessment of Energy Products: Environmental Assessment of Biofuels*; Empa: Gallen, Switzerland, 2007. Available at http://www.globalbioenergy.org/bioenergyinfo/bioenergy-and-climate-change/detail/en/news/3966/icode/7/.

(117) Hecht, A. D.; Shaw, D.; Bruins, R.; Dale, V.; Kline, K.; Chen, A. Good policy follows good science: using criteria and indicators for assessing sustainable biofuel production. *Ecotoxicology* **2008**, *18*, 1–4.

(118) Roundtable on Sustainable Biofuels. *Version Zero - Global Principles and Criteria for Sustainable Biofuels Production*; RSB, 2008. Available at http://cgse.epfl.ch/page79931.html.

ES900250D