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Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production

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Abstract

The Energy Independence and Security Act of 2007 set an annual US national production goal of 39.7 billion l of cellulosic ethanol by 2020. This paper explores the possibility of meeting that target by growing and processing Miscanthus × giganteus. We define and assess six production scenarios in which active cropland and/or Conservation Reserve Program land are used to grow Miscanthus. The crop and biorefinery locations are chosen with consideration of economic, land-use, water management and greenhouse gas (GHG) emissions reduction objectives. Using lifecycle assessment, the net GHG footprint of each scenario is evaluated, providing insight into the climate costs and benefits associated with each scenario’s objectives. Assuming that indirect land-use change is successfully minimized or mitigated, the results suggest two major drivers for overall GHG impact of cellulosic ethanol from Miscanthus: (a) net soil carbon sequestration or emissions during Miscanthus cultivation and (b) GHG offset credits for electricity exported by biorefineries to the grid. Without these factors, the GHG intensity of bioethanol from Miscanthus is calculated to be 11–13 g CO₂-equivalent per MJ of fuel, which is 80–90% lower than gasoline. Including soil carbon sequestration and the power-offset credit results in net GHG sequestration up to 26 g CO₂-equivalent per MJ of fuel.

Keywords: biofuels, ethanol, Miscanthus, greenhouse gases (GHG), lifecycle assessment (LCA), scenarios

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1. Introduction

In portfolios of renewable energy technologies, bioethanol has remained one of the most promising alternatives to petroleum-based transportation fuels. Corn and sugarcane are currently the dominant feedstocks. However, research suggests that ethanol produced from lignocellulosic materials such as perennial grasses and agricultural or forestry residues can achieve lower lifecycle carbon emissions and avoid adversely impacting food prices (Somerville et al 2010, Farrell et al 2006, Tilman et al 2006). In this context,
the Energy Independence and Security Act of 2007 (EISA) requires an aggressive scale-up of cellulosic biofuels as part of the Renewable Fuel Standard (RFS) program, with a production target of 39.7 billion 1 yr\(^{-1}\) (10.5 billion gal yr\(^{-1}\)) by 2020 (US EPA 2009). However, the environmental impacts of any biofuel depend not only on the type of feedstock, but also on how and where it is grown, processed and transported (McKone et al 2011). Through scenario development and analysis, our research seeks to assist decision-makers in understanding and limiting the GHG footprint of lignocellulosic biofuels, while also protecting water resources, human health and ecosystems.

Lignocellulosic biomass to ethanol pathways have yet to be realized on a commercial scale, so choices about the feedstocks, types of land cultivated, biorefinery technologies, and transportation and storage infrastructure remain speculative. These choices can substantially influence the expected carbon footprint of ethanol. To be proactive in assessing the Miscanthus-to-ethanol pathway’s potential environmental impacts, researchers must make educated guesses about these choices. This paper focuses on the potential for growing and processing Miscanthus x giganteus, a high-yield perennial grass, on active cropland and on Conservation Reserve Program (CRP) land in the United States. Scenario analysis provides an opportunity to explore a range of options and to identify which choices will be strongly influential in determining the climate (and other) impacts of ethanol production. Large-scale scenarios for cellulosic ethanol production have been published (US DOE 2008, Perlack et al 2005, Morrow et al 2006); however, to date they have focused only on single phases of the system (biomass production or ethanol distribution, for example).

To understand the full lifecycle impacts of producing cellulosic ethanol, each major phase must be considered in an assessment: biomass production, farm to biorefinery transportation, biorefining, and biorefinery to fueling station transportation.

Considering each of these lifecycle stages from farm to tank, this paper presents an evaluation of six US national scenarios for cellulosic ethanol production, each with different land conversion objectives and constraints. All six scenarios assume conversion to ethanol via dilute-acid pretreatment and enzymatic hydrolysis at levels designed to meet the EISA 2020 cellulosic ethanol production goal of 39.7 billion 1 yr\(^{-1}\) (10.5 billion gal yr\(^{-1}\), corresponding to fuel energy production rate of 0.929 EJ yr\(^{-1}\)). We define and use the scenarios presented in this paper to explore several important environmental and economic aspects of large-scale cellulosic ethanol production: minimizing conversion of active cropland to Miscanthus, avoiding excessive drought risk, maintaining economic efficiency by minimizing the market value of active cropland converted, and maximizing carbon credits for biorefinery power exports. The resulting lifecycle GHG footprint for each scenario is evaluated. The outcomes are compared to show how aiming to satisfy alternative objectives can influence the carbon intensity of cellulosic ethanol production.

2. Methods

For evaluating lifecycle greenhouse gas consequences of biofuels, where the feedstock is grown matters because farm locations dictate where biorefineries are sited and how far both the biomass feedstock and the ethanol product will have to be transported. Desirable goals for Miscanthus cultivation include low competition with food production, low impact on constrained water resources, low encroachment on wildlife habitat, and low GHG release associated with stored soil carbon, biomass growth and harvesting cycles. At the same time, it is necessary to achieve sufficiently high yields to maintain farm profitability. It may not be possible to simultaneously satisfy all of these aims. We consider here two classes of land that are potentially suitable for large-scale Miscanthus production: active cropland and CRP land. In the scenario definition and analysis, all data for cropland and CRP land are defined and utilized at the county level.

2.1. Scenario development

Many biofuel feedstocks are available, which can in turn be converted using many different production pathways to many different fuels. The Miscanthus-to-ethanol pathway was chosen for this paper both because of Miscanthus’ promise as a feedstock and because of the relatively mature state of technology for biochemical conversion of herbaceous biomass to ethanol compared to other cellulose conversion processes. Miscanthus, which utilizes C\(_4\) photosynthesis, is efficient in its use of nutrients, energy and water to produce biomass, and can be grown on low quality or marginal land (Somerville et al 2010, Ainsworth et al 2008, Miguez et al 2008). Also, the scalability of dedicated crops such as Miscanthus is key for achieving biofuel production goals because crop residues alone cannot provide enough ethanol to displace gasoline in the United States. For example, corn stover is the single most plentiful crop residue available in the United States. If the most optimistic annual production estimate of 232 dry Tg (256 million tons yr\(^{-1}\)) (Perlack et al 2005, Perlack and Stokes 2011) is combined with the most recent ethanol yield estimate of 330 million l/Tg (79 gal/ton) (Humbird et al 2011), total potential ethanol production from corn stover would be approximately 77 billion l yr\(^{-1}\) (20 billion gal yr\(^{-1}\)), just 11% of projected gasoline demand in 2020.

A significant concern identified for large-scale biofuel production is indirect land-use change (iLUC), which when induced sufficiently can push the GHG footprint of biofuels to levels well above those of gasoline and diesel (Searchinger et al 2008). To the extent that Miscanthus can be grown on land that is otherwise unused, the iLUC impacts can be avoided. Determining what land in the United States is truly non-productive is a difficult task in itself, as the term ‘idle cropland’ can refer to a variety of long- and short-term cropland management techniques (Lubowski et al 2006). By definition, CRP land in the United States does not produce any agricultural products; farmers voluntarily enter into contracts with the federal government with 10–15 year terms, during which time they are paid not to grow on their
Power-offset credit is maximized by limiting active cropland conversion and non-baseload GHG emission factor. Constraints entail relatively high mean market values of converted active cropland ($6170–$8260/ha) and require 7.5–8.8 million ha of all active US cropland, Scenarios 2–4 convert only active corn land, and Scenarios 5–6 convert all available active cropland to meet the 39.7 billion l per year cellulosic ethanol US production goal for 2020.

| Scenario No. | Active cropland | Active corn land | CRP and active cropland |
|-------------|-----------------|------------------|-------------------------|
| Minimize    | N/A             | N/A              | N/A                     |
| Maximise    | N/A             | Net ethanol production increase | Net ethanol production increase |
| Constraints | N/A             | N/A              | Avoid drought-prone counties and ensure large power-offset credit$^a$ |
| Total land converted (million ha) | 7.9 | 8.0 | 7.5 | 8.8 |
| Active cropland mean value (2007 USD/ha) | 8060 | 6170 | 8260 | 8100 | 3630 | 4050 |

$^a$ Power-offset credit is maximized by limiting Miscanthus growth and processing to the MRO NERC region, which has the highest non-baseload GHG emission factor.

$^b$ Power-offset credit is maximized by limiting active cropland conversion and Miscanthus processing to the MRO, SERC and RFC NERC regions, which have the top three non-baseload GHG emission factors. CRP land remains fully utilized.

Table 1 summarises each scenario and figure 1 presents maps of the associated county-by-county Miscanthus production. Data used to develop the scenarios are documented in the supporting information (available at stacks.iop.org/ERL/7/014011/mmedia for methods and detailed results). To ensure economic viability, all scenarios are subject to a no-irrigation constraint, which limits Miscanthus cultivation to roughly the eastern half of the United States. Among the six scenarios, all of which meet the EISA goal of 39.7 billion l of cellulosic ethanol per year, there are three main land conversion strategies: Scenario 1 converts a uniform percentage (12%) of all active US cropland, Scenarios 2–4 convert only active corn land, and Scenarios 5–6 convert all available CRP land plus active cropland with the lowest market value. Within the main land conversion strategies, individual scenarios explore the possibility of achieving economic efficiency by minimizing the purchase price as defined by USDA (2010) of active cropland converted, maximizing the net yield benefit of Miscanthus over corn for active corn land (ethanol produced per ha of cropland), avoiding excessive drought risk and maximizing the net reduction in GHG emissions resulting from bioenergy power exports. Scenario analysis reveals a tradeoff between economic efficiency and total land requirements. Scenarios 1–4 entail relatively high mean market values of converted cropland ($6170–$8260/ha) and require 7.5–8.8 million ha...
of land. Scenarios 5–6, which convert CRP and low-value cropland, require approximately twice the amount of land (16–18 million ha), but do so with much lower market values of converted cropland ($3630–$4050/ha). Including the environmental goals of avoiding excessive drought risk and maximizing the biorefinery GHG credit for power exports adversely impacts the total land requirements and mean market values of converted active cropland. Relative to Scenario 2, environmental constraints in Scenario 4 increase the land requirement by 10% and the mean market value of converted land by 31%. Including environmental goals in Scenario 6 results in a 7.3% increase in total land required and a 12% increase in the mean market value of active cropland converted relative to conditions in Scenario 5.

2.2. Lifecycle inventory of greenhouse gas emissions

Having explored several land conversion alternatives, we now turn to the issue of assessing GHG emissions. To do so, we employ a lifecycle assessment (LCA) approach (summarized in figure 2) to estimate the net change in environmental impacts that result from some change in human activity, in this case, the addition of cellulosic ethanol production. Market effects, such as petroleum or land price changes resulting from increased fuel ethanol production, are outside the scope of this study and are thus excluded. Quantifying the net change in GHG emissions caused by increasing cellulosic ethanol production from Miscanthus informs decision-makers as to whether such a path could yield climate benefits relative to
Figure 2. Scope of lifecycle inventory of greenhouse gas emissions. Dashed lines denote biogenic carbon that is part of a closed cycle. Indirect land-use change and other market effects are not included.

Beginning with the biomass production stage, there are three main contributors to the GHG footprint: combustion of liquid fuels in farm equipment, upstream emissions from the manufacturing of chemical inputs such as fertilizers, and the flux of carbon between soil and the atmosphere. Five different pieces of farm equipment are used to harvest Miscanthus: tractor, mower, baler, bale loader and stinger (for bale transport). Together, they are estimated to contribute 13 kg of CO₂e per Mg of biomass harvested (see supporting information available at stacks.iop.org/ERL/7/014011/mmedia for details). A portion of Miscanthus is lost during each handling stage, such that only 72% of the original dry biomass is expected to reach the biorefinery (Shastri et al 2010). We assume lost biomass decomposes to CO₂; significant formation of CH₄ would result in greater GHG emissions during the biomass production phase. Recent empirical results suggest that CH₄ fluxes for soil under Miscanthus are negligible (Drewer et al 2011). Unlike most food crops, Miscanthus is expected to require manufactured fertilizer and herbicide only during the establishment year, with ash from biorefineries applied as fertilizer in subsequent years (Oliveira et al 2001, Huisman et al 1997, Carroll and Somerville 2009). Over the assumed 15-year crop lifetime, normalized GHG emissions associated with fertilization and herbicides per Mg of biomass harvested are relatively small.
However, some experimental results indicate that regular application of nitrogenous fertilizer may be needed to avoid depleting soil N over time, which would increase both upstream fertilizer-related GHG emissions and on-field N$_2$O emissions (Christian et al. 2008, Drewer et al. 2011).

After being baled and dried, the biomass is trucked to biorefineries. The biorefinery analysis is based on the National Renewable Energy Laboratory’s updated report on dilute-acid pretreatment and enzymatic hydrolysis of corn stover (Humbird et al. 2011). Previous analysis has shown that switching the input from corn stover to Miscanthus for this conversion process does not substantially change the results (Bhattacharjee 2010). Because the lignin from Miscanthus can be burned within the biorefinery to satisfy its process heat and electricity requirements, no grid electricity or fossil fuel inputs are required (Humbird et al. 2011). Biorefineries are also expected to produce enough power to become net exporters to the grid; this aspect is discussed later.

Ethanol transport from biorefineries to fueling stations depends on the distribution of biorefinery locations, the geographical distribution of gasoline demand (since most ethanol is mixed with gasoline) and the blend wall, which refers to the maximum allowable percentage of ethanol in general-use motor fuel. The US blend wall is currently set at 10% ethanol (E10), although the US EPA has approved E15 for vehicles manufactured later than 2001 and existing flex-fuel vehicles are compatible with E85. Transportation distances were calculated using 2009 state-level gasoline consumption data for the 48 contiguous states, with an assumed maximum future average blend of E20. The calculations were made assuming that suppliers minimize total transport distances. The mass-weighted apportionment of biofuel transportation modes was assumed to be constant across all scenarios: 70% rail, 5% domestic marine and 25% truck.

3. Results and discussion

Lifecycle greenhouse gas emissions were evaluated for six scenarios of large-scale cellulosic ethanol production. Each scenario was designed to yield 929 billion MJ yr$^{-1}$ of new cellulosic ethanol and the scenarios were varied to explore a range of realistic environmental and economic constraints. Overall, the results (figure 3) exhibit some sensitivity to the assumptions embedded in the scenarios. However, a major finding is that the lifecycle GHG emissions intensity associated with cellulosic ethanol is at least 80% lower than that of gasoline, provided that iLUC impacts can either be avoided or kept small. The results also reveal two major drivers for cellulosic ethanol’s GHG footprint, both of which contribute significant uncertainty: (a) soil carbon net sequestration or emission rates and (b) the electric power-offset credit. For example, assumptions related to these two factors cause the GHG footprint for Scenario 4 to range between $\pm$26 and $+22$ g CO$_2$e emitted per MJ of ethanol energy produced. Soil carbon net sequestration or net emissions depend on the type of land used to grow Miscanthus and on the timescale of analysis. The electric power-offset credit depends on biorefinery location, as well as on economic and policy factors that affect which existing forms of power generation are displaced when biorefineries sell power to the electrical grid.

Soil carbon fluxes are known to be significant in magnitude, but depend on many soil- and site-specific factors and are thus difficult to predict. The ability to sequester atmospheric carbon into soil is one of the characteristics that makes perennial grasses such as Miscanthus attractive (Tilman et al. 2006). Soil that has been depleted of carbon has enhanced sequestration potential (Watson et al. 2000). Actively farmed cropland contains 20–50% less soil carbon than would exist in its natural state (Mann 1986, Schlesinger 1986, Davidson and Ackerman 1993). This land can sequester carbon if left untillled or if planted with a grass such as Miscanthus. However, sequestration associated with growing Miscanthus on depleted soils would not be expected to continue indefinitely. Rather, such restoration activities should result in net carbon sequestration until the soil reaches sink capacity after a 20–50 year period (Odum 1969, Johnson 1995, Watson et al. 2000). CRP land that has been previously farmed also sequesters carbon over time, at a rate that depends on the type of cover crop or other vegetation that is allowed to grow while the land is out of production. Consequently, replacing CRP land with Miscanthus may result in net carbon sequestration, in net emissions, or in no net change, depending on details of the usage history, including what had been grown on the land, for how long the land has been out of production and the types of vegetation currently growing.

To explore the significance of soil carbon sequestration in this study, two timescales are considered: short term and long term. In the short term, when carbon-depleted soils have not yet been restored to their carbon sink capacity, net carbon accumulation is approximated as linear. The long-term results consider land that has been producing Miscanthus for decades, such that there is no net soil carbon sequestration. For CRP land, we assume that the carbon sequestration rate achieved by Miscanthus is not substantially different from that which could be achieved by simply remaining in CRP and growing either cover crops or native vegetation. Hence, the net change in soil carbon sequestration resulting from planting Miscanthus on CRP land relative to the status quo is approximated as nil. It also should be noted that soil carbon lacks inherent permanence. If land whose soil carbon has been restored by Miscanthus is later converted back to tilled farmland, at least some of those gains would be lost to the atmosphere (Khanna et al. 2007). More research on factors influencing soil carbon fluxes is needed to gain insight into how biofuel crops would affect carbon levels in soil. Given the current state of knowledge, we believe that the fluxes incorporated into our analysis are reasonable estimates.

After Miscanthus is harvested and transported to biorefineries, we assume that the lignin fraction of the biomass is burned beneficially, for process heat and electricity generation. Each biorefinery has the capacity to generate more than enough electricity to satisfy its own internal needs. For every MJ of ethanol produced, it is expected that 0.09 MJ of excess electricity can be sold to the grid.
Figure 3. Lifecycle greenhouse gas emissions intensity for cellulosic bioethanol. The analyses account for soil carbon sequestration and the biorefinery power-offset credit. The ‘short-term’ conditions apply during the first 2–5 decades of wide-scale Miscanthus deployment whereas ‘long-term’ results apply after the soil no longer exhibits a net uptake of carbon. Consequences of indirect land-use change are not considered in this analysis.

(Humbird et al. 2011), yielding a power-offset credit to be accounted for in LCA. Which power plants would be displaced by biorefinery-produced electricity has a significant impact on the GHG emissions associated with cellulosic ethanol production, as well as other impacts such as water use (Scown et al. 2011). Choosing appropriately requires detailed electrical grid models and depends on assumptions about future policies. For example, if biorefinery power exports contribute to meeting targets of Renewable Portfolio Standards (RPS), they may displace other renewable electricity sources such as solar or wind. If the exports occur in locations without RPS, or do not qualify, then they would likely offset the most expensive (and easiest to control) power plants, i.e., the non-baseload plants. The US EPA provides estimates of carbon intensity for non-baseload electricity in its eGRID online US power plant database (summarized in the supporting information available at stacks.iop.org/ERL/7/014011/mmedia), although the documentation for these factors is sparse (US EPA 2011). Natural gas-fired power plants often serve as an approximation of non-baseload power because natural gas plants can be dispatched quickly. In this paper, the GHG intensity of natural gas is calculated by taking the production-weighted average of all natural gas-fired power plants in each NERC region. To account for uncertainty associated with power-offset credits, three displacement cases—renewables, eGRID non-baseload and natural gas-fired plants—are explored in the results. A fourth case explores the possibility of no power generation, in which case biorefineries must draw eGRID non-baseload power from the grid. It is also plausible that biorefineries would generate electricity to meet their own needs, but not export power owing to infrastructure constraints; in this instance, the results would be identical to those of the renewables offset credit case. The differences among these cases are striking, in some cases causing the GHG footprint not only to decline, but even to change sign from net emissions to net sequestration, e.g., from +22 g CO₂e/MJ ethanol to −2 g CO₂e/MJ ethanol.

Figure 3 depicts GHG emission intensity results for each of the six scenarios. Within each scenario, the differences in bar heights indicate the sensitivity of the results to the power-offset credit. Comparing the short-term results to the long-term results for a given scenario indicates sensitivity to expectations regarding soil carbon sequestration. These results suggest that if Miscanthus is planted on active cropland, the near-term potential for net soil carbon sequestration is large and will likely result in a net negative GHG footprint for cellulosic ethanol during the first 2–5 decades of production. The power-offset credit also presents an important opportunity for maintaining a low or even net negative GHG footprint, particularly if biorefinery power exports can be used to displace fossil fuel-fired power plants rather than other renewable electricity generation. On the other hand, if power exports qualify as renewable electricity and can thus be sold to the grid at a higher price, the ethanol producers will benefit, which could accelerate the development of cellulosic ethanol toward the target scale.

Excluding soil carbon sequestration and the power-offset credit, the remaining GHG footprint of cellulosic ethanol is mainly associated with biomass production and transportation; the net GHG emissions associated with biorefining are an order of magnitude smaller. Figure 4 illustrates the results. Each bar in the figure is divided into direct and upstream emissions, denoting whether the emissions occurred on-site (direct) or upstream (e.g., at a chemical manufacturing facility). A full summary of results is presented in the supporting information (available at stacks.iop.org/ERL/7/014011/mmedia). Compared to lifecycle studies of a similar pathway, switchgrass-to-ethanol, the GHG results in the present study are significantly lower because the earlier reports do not account for soil carbon sequestration or for a power-offset credit (Bai et al. 2010, Spatari et al. 2005). Excluding soil carbon and power exports, Spatari et al. (2005) estimate biomass phase GHG emissions of 19 g
Figure 4. Greenhouse gas emissions for each lifecycle phase, considering separately direct and upstream emissions. Soil carbon sequestration and the power-offset credit are excluded.

$\text{CO}_2\text{MJ}^{-1}$ as compared to 6.5–7.2 g $\text{CO}_2\text{MJ}^{-1}$ in this paper. The differences result from an assumption by Spatari et al of higher fertilizer application and the inherently lower yield of switchgrass relative to *Miscanthus*. Spatari et al (2005) also report substantially lower transportation-related emissions owing to smaller assumed distances and also the exclusion of upstream emissions. Upstream emissions are often ignored or underestimated in environmental assessments and can be particularly important for transportation (Chester and Horvath 2009), in this case comprising nearly a third of total transportation-phase emissions. In biorefining, all GHG emissions are treated as upstream, because all of the $\text{CO}_2$ emitted directly from the facilities is biogenic and would be recovered when *Miscanthus* is regrown. The upstream emissions from biorefining are largely attributable to the production of chemicals used in high volumes such as sulfuric acid. Although there is less uncertainty associated with impacts not related to soil carbon or electric power-offset credits, increases in scale may cause the GHG footprint of some lifecycle phases to change. For example, if the ethanol industry were to achieve production volumes sufficient to justify dedicated pipelines, then the transportation-related emissions would decrease significantly.

Even at the assumed level of deployment in the scenarios considered in this paper, cellulosic ethanol would still constitute a small fraction of total transportation energy demand in the United States, for example, as compared to the projected gasoline consumption of 16 trillion MJ year$^{-1}$ in 2020. Although the scale of cellulosic ethanol is modest in this context, the scenarios indicate that the *Miscanthus*-to-ethanol production pathway has the potential to provide some climate benefits while also reducing the need for fossil fuel-burning power plants and improving the quantity of soil carbon sequestered in agricultural soils. For crops such as switchgrass and *Miscanthus*, which cannot be widely grown in the western half of the country owing to water constraints, the amount of CRP land available is not enough to eliminate the need for some conversion of active cropland, even to meet the 2020 cellulosic ethanol production goals. To ensure that *Miscanthus* and other dedicated biomass crops do not compete significantly with food crops and also achieve their intended climate and ecological goals, a comprehensive national land management strategy is critically important. Nevertheless, if combined with agricultural residue such as corn stover, as well as more drought-tolerant, water-saving biomass feedstocks that can take advantage of CRP land in the western US, cellulosic ethanol has the potential to become a meaningful contributor to the future of transportation energy.

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