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Assessing land-use impacts by clean vehicle systems

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ABSTRACT

Transition of the current gasoline-based transportation system into a renewable fuel-based clean vehicle system has the potential to reduce greenhouse gas emissions and improve national energy security. However, the realized net environmental benefit or energy security improvement is tightly linked to the electricity fuel mix (for electric cars and plug-in hybrids) and fueling strategy (for cars using alternative liquid fuels). In addition, different types of transportation fuels have significantly different demands on land resources, both on land type and quantity. For example, biofuel production requires large quantities of agricultural land, while wind farms require land with sufficient wind density. Furthermore, there is substantial regional variation in the quality of necessary resources. Regions with higher wind speeds require less land to produce the same amount of electricity than those with lower wind speed, assuming the same turbine design. Similarly, regions with optimal soil conditions and climate for crop cultivation require less land to produce the same amount of biofuel. To enable comparison of land demand among different fuel choices for clean vehicles, this research provides a county-scale assessment of land demand based on a "per-vehicle-mile-traveled" basis. Potential clean vehicle fuels assessed in this study include ethanol produced from different feedstocks (corn and switchgrass), biodiesel from algae cultivated in open ponds and closed systems, and electricity produced from renewable sources (wind and solar). Our results show that, in general, engineered systems (wind electricity, solar electricity, and biodiesel from closed-system algae) are more land efficient than natural systems (corn ethanol from corn starch and stover, switchgrass ethanol, and biodiesel from open-pond algae). Solar electricity is the dominant regional optimal fuel choice from the land-use perspective for engineered systems while lowland switchgrass ethanol and biodiesel from open-pond algae are the major optimal choices for the natural systems. These results shed light on developing both federal and state level policies to minimize land-use impact for the development of a clean vehicle system.

1. Introduction

A renewable fuel-based U.S. transportation system has the potential to address climate change and energy security issues by reducing greenhouse gas (GHG) emissions and alleviating dependence on foreign oil imports. In 2011 over 27 quadrillion Btu of energy, almost one-third of total U.S. energy consumption, was attributed to the U.S. transportation system (U.S. Department of Energy EIA, 2013a). The current transportation system is highly dependent on gasoline, with 93% of transportation energy sourced by petroleum, making the transportation sector particularly vulnerable to disruptions in oil markets (Congressional Budget Office, 2012; U.S. Department of Energy EIA, 2013b). In addition, the transportation sector is one of the major contributors for GHG emissions, responsible for over 1800 million metric tons of CO_2 equivalent in 2011 (U.S. Department of Energy EIA, 2013b; U.S. EPA, 2013). Various federal and state policies were enacted to facilitate renewable fuel production in order to change these trends. The policies particularly driving this research are the updated national-level Renewable Fuel Standard (RFS2) which was passed as part of the Energy Independence and Security Act of 2007, and the various

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state-level Renewable Portfolio Standards (RPS) (Congress, 2007; NREL, 2008; Schnepf and Yacobucci, 2010). The RFS2 mandates that a minimum 36 billion gallons of biofuels be used in the U.S. transportation system by 2022, and includes specific requirements for corn ethanol, cellulosic biofuels, and advanced biofuels (Schnepf and Yacobucci, 2010). RPS mandates vary by state but generally require a certain percentage of state energy to come from renewable sources, like wind and solar electricity, by a certain year (DSIRE, 2014). Although the RPS mandates are not limited to transportation energy, they will likely affect the electrical grid mix and therefore will play a role in renewable energy development for clean vehicle systems.

Clean vehicles refer to vehicles that use alternative fuels instead of gasoline or diesel. Promising renewable fuels for clean vehicle systems include bioethanol (e.g. from corn starch, corn stover and switchgrass), biodiesel (e.g. from algae), and electricity generated from renewable sources (e.g. solar and wind). Depending on the fuel type and source, each fuel option has different advantages and disadvantages. Corn starch based ethanol can leverage existing fueling infrastructure and engines when blended with gasoline, but competes with food supply and may not significantly reduce net energy use and GHG emissions over the lifecycle of fuel production and use (Geyer et al., 2013; Schnepf and Yacobucci, 2010). Ethanol from cellulosic feedstock such as switchgrass is often considered more promising because switchgrass maintains high yields in a variety of growing conditions, including on marginal lands, and does not compete with food (Valentine et al., 2012). However, the cellulosic ethanol conversion process is still costly and highly uncertain, requiring significant research and investments to reach the commercial scale (Gunderson et al., 2008; Schnepf and Yacobucci, 2010). Biodiesel extracted from algae boasts a high energy yield but will also require a considerable amount of research to reach industrial-scale production levels and its production raises concerns about high water and nitrogen requirements (Quinn et al., 2012; Wigmosta et al., 2011). Renewable electricity from wind and solar has a better record for reducing energy use and GHG emissions with fewer environmental concerns, but its development faces uncertainties with electricity storage/transmission and trade-offs related to high technology and infrastructure costs (Arent et al., 2011). Therefore, uncertainties and trade-offs exist with the development of renewable transportation fuels. A better understanding of the advantages and disadvantages of different fueling strategies for a clean vehicle system is necessary to inform policy decisions and avoid negative unintended consequences.

In addition, large scale renewable transportation fuel production could significantly impact natural resource demand, such as water (Cai et al., 2013; Chiu and Wu, 2012) and land (Elliott et al., 2014; McDonald et al., 2009). McDonald et al. (2009) estimate that the land-use intensity of biofuels will continue to be 10–20 times more than that of conventional fossil fuels into the year 2030, suggesting that the development of a clean vehicle system may have a profound demand for land (McDonald et al., 2009). The authors also estimate that to meet the RFS2 alone will require upwards of 206,000 km^2 of new land devoted to biofuel development (an area larger than the state of Nebraska) (McDonald et al., 2009). The expansion of renewable fuel production can cause direct and indirect land-use change that potentially lead to increasing deforestation, loss of biodiversity, and increased GHG emissions (Dunn et al., 2013; Lambin and Meyfroidt, 2011; Rathmann et al., 2010; Sarkar and Miller, 2014; Searchinger et al., 2008). Furthermore, this impact could be more significant at the regional scale because the land-use intensity (the amount of land required to produce one unit of fuel) of potential renewable transportation fuels is not only significantly different depending on the fuel type, but also varies geographically due to climatic and topographical conditions. Because transportation infrastructure development is path dependent, it is important for policy makers to consider potential land-use impact when planning for fueling strategies for regional clean vehicle system development. However, much of the current literature regarding renewable transportation fuels focuses on net energy use and life cycle GHG emissions of each individual fuel (Fthenakis and Kim, 2009; Miller, 2010) and average land requirement based on different units (Cherubini et al., 2009; Fthenakis and Kim, 2009; Geyer et al., 2013; Horner and Clark, 2013; Miller, 2010). Little attention has been paid to regional fueling strategies from the perspective of minimizing land-use impact. This research aims to fill this gap by comparing land-use demand of different renewable transportation fuels at regional scale and identify land-efficient fueling options.

This research compares the direct land-use intensities of different renewable fuels by assessing land-use on a “per-vehicle-mile-traveled” basis. In other words, the amount of land required to be occupied for a year to fuel a light-duty vehicle to travel one mile (for simplicity, the unit of m^2/VMT is used in this paper). The land-use intensities are measured on a county-level basis to assess regional variations for each renewable fuel, as well as the regional variation in the optimal renewable fuel choice. Understanding regional patterns of land-use intensities among renewable fuel alternatives and the land demand to meet travel demand on renewable fuels will aid implementation of policies like the RFS2 and RPS by helping states develop better fueling strategies. Because transportation infrastructure development is path dependent, fueling strategy decisions made today will have impacts on regional resources and energy uses in the long term.

2. Materials and methods

2.1. Land-use intensity and efficiency

In this study, land-use intensity is defined as the amount of land needed to produce enough fuel in a year to power one mile of vehicle travel (m^2/VMT). Using one vehicle-mile-traveled (VMT) as the reference unit is a common approach to enable comparison of land-use demand of different renewable transportation energy options (Choudhary et al., 2014; Geyer et al., 2013). The system boundary includes only the land needed for crop cultivation or electricity generation. Indirect land demand (e.g. road for fuel transportation, extraction or mining of raw materials) is not accounted for because they are insignificant compared to direct land-use for energy generation (Fthenakis and Kim, 2009). Land-use efficiency is the complementary way of describing land-use intensity in this study. Higher land-use efficiency indicates lower land-use intensity and vice versa. The renewable transportation fuel options examined in this research include: (1) corn ethanol (from both corn starch and stover), (2) lowland switchgrass ethanol, (3) upland switchgrass ethanol, (4) biodiesel from open-pond algae, (5) biodiesel from closed-system algae, (6) solar photovoltaic electricity, and (7) onshore wind electricity. These options were chosen to represent the different categories of fuels mandated in the RFS2 and the most common and promising renewable electricity sources. This research studies county-level land-use intensity of above mentioned fuels in contiguous states, including the District of Columbia. Spatial variations of productivity of each fuel option impacted by factors including radiation, soil quality, temperature, and wind speed, are incorporated in the analysis. We use 0.35 kWh/mile vehicle fuel economy (DOE, 2013) and 0.88 charging efficiency (Kelly et al., 2012) for electric vehicles. Corporate Average Fuel Economy (CAFE) standards of light-duty vehicles in 2011 at 30 mpg for gasoline vehicles is used as the baseline for liquid fuels (Bureau of Transportation Statistics, 2011; EPA, 2012). Fuel economies of ethanol and biodiesel are modified based on heat contents relative to gasoline (116,090 btu/gal).

2.1.1. *Corn-derived ethanol*

Ethanol can be produced from both corn grains and corn stover, through different pathways. After harvested from the field, corn grains are transported to ethanol plants where corn grains are milled and the starch is fermented to produce ethanol (Wang et al., 2011). Corn stover is the residual biomass from corn grain harvest and is a type of cellulosic feedstock. Therefore, ethanol production from corn stover is more complicated and requires enzyme-catalyzed hydrolysis before fermentation (Spatari et al., 2005). However, not all corn stover is available for ethanol production because complete removal of corn stover from the fields can cause soil erosion, reduce soil carbon, and decrease corn yield (Liska et al., 2014).

In this study, we used county level average corn grain yield data reported by the United States Department of Agriculture (United States Department of Agriculture, 2011) and production efficiency of 2.8 gallons of ethanol per bushel of corn (Oak Ridge National Laboratory, 2011) to calculate ethanol production from corn starch. Because corn-soybean rotation is a common practice in the field, the real world yield data already reflect the impact of crop rotation on corn yield. Corn stover derived ethanol is estimated based on a harvest index (weight of grain to the total weight of grain and stover) of 0.5 (Spatari et al., 2005), a minimum requirement of 2.3 dry ton/acre corn stover to maintain soil organic carbon (Pioneer Agronomy Sciences, 2011), and an ethanol production efficiency of 340 L/dry ton (Sheehan et al., 2003). If corn stover yield is less than 2.3 dry ton/acre, then no corn stover will be removed from the field in that region for ethanol production. Ethanol produced from both corn grains and stover is combined to calculate land-use intensity for corn ethanol using ethanol energy density of 76,330 btu/gal (Alternative Fuels Data Center, 2012).

2.1.2. *Switchgrass-derived ethanol*

There are two ecotypes of switchgrass: lowland and highland. The lowland ecotype generally grows taller, thicker, and is found in wetter southern habitats. The upland ecotype is shorter, thinner, and is more tolerable for drier and cold weather (Gunderson et al., 2008; Thomson et al., 2009). Biomass yield depend on not only the ecotypes but also the climate, soil type, etc. (Tulbure et al., 2012). Switchgrass yields by county measured in Mg/ha for both upland and lowland ecotypes were obtained from a predictive model, developed by Oak Ridge National Lab, based on the relationship between observed yields and climatic conditions (Gunderson et al., 2008). Areas with yield less than 1 Mg/ha were considered unsuitable for switchgrass ethanol development and were excluded (Gunderson et al., 2008; Jager et al., 2010). The predicted yields represent a theoretical upper limit under regional climate conditions with no additional irrigation and nutrient application. In the real world, while irrigation and nutrients can be applied, regional field data and results from other projections are comparable to these values (Jager et al., 2010; Thomson et al., 2009). Land-use intensity of switchgrass based ethanol was calculated based on an ethanol yield of 380 L/ton of switchgrass (Thomson et al., 2009), and ethanol energy density of 76,330 btu/gal.

2.1.3. *Biodiesel produced from algae*

Algae as a biofuel feedstock can be cultivated in both open-ponds and closed-systems (i.e. photobioreactors). While closed-systems can protect algae growth from invasive species, reduce water loss due to evaporation, and maintain higher temperature during cold weather, open-ponds are generally more economically feasible (Wigmosta et al., 2011). Annual average biodiesel yields (in L/ha) from algae cultivated in open-ponds were obtained from a Pacific Northwest National Lab (PNNL) study that estimated potential biofuel production using physics-based biomass growth and pond temperature models with location-specific meteorological and topographic data (Wigmosta et al., 2011). Areas determined to be unsuitable for open-pond algae (e.g. land with steep slope), as well as areas containing open water, were excluded. Annual average biodiesel yields from algae cultivated in photobioreactors (closed-system algae) were obtained from Quinn et al. (2012), which were estimated using a model of microalgae growth combined with thermal models of the photobioreactor system and historical weather data (Quinn et al., 2012). Land-use intensities of both biodiesels were calculated assuming an algae biodiesel energy density of 121,000 btu/gal.

2.1.4. *Solar photovoltaic electricity*

Annual average daily total solar resource in kWh/m^2/day from 1998 to 2009 for the contiguous U.S. was obtained from the National Renewable Energy Laboratory (NREL, 2012). The solar resource was averaged over surface cells of 10 km resolution at tilt equal to latitude. Land-use intensity of solar electricity was calculated based on a 9% module efficiency (Geyer et al., 2013; Kim et al., 2012; Masters, 2004), 0.7 performance ratio (Fthenakis et al., 2011; Kim et al., 2012), 0.2 land occupation ratio (ratio of actual occupation of solar panels to total land footprint) (Castro et al., 2013), and 10% transmission and distribution losses (Delucchi and Jacobson, 2011).

2.1.5. *Wind electricity*

Annual average wind resource potential for the contiguous U.S. was also obtained from the National Renewable Energy Laboratory (NREL, 2011). The data represent wind power class at 50 m height above surface with 25-km resolution. Areas with wind power classes 1 and 2 were excluded due to unsuitability for wind power development. Wind power density of 5 MW/km^2 (Lopez et al., 2012) and capacity factors of 0.32, 0.36, 0.41, 0.44, and 0.46 for wind class 3–7 respectively (Black & Veatch Corporation, 2012) are used to calculate land-use intensity. Transmission and distribution losses of 10% are included (Phillips and Middleton, 2012). This research only considers onshore wind because offshore wind does not compete with other alternative fuels for land resources.

2.2. *Regional optimal choices selection*

The optimal renewable fuel choice in each county was selected by identifying the fuel option with the lowest land-use intensity value among all options examined in this study. Because wind data have a finer resolution than county, for areas in which wind energy is available, the area of wind energy was used for comparison rather than the county area.

2.3. *Sensitivity analysis*

To test the sensitivity of regional optimal choices to the land-use intensity of each fuel option, we examined the optimal choice change in response to land-use efficiency change for each of the fuel choices at both the aggregated level and the county level. At the aggregated level (national), we used the percent of land area having each fuel option as the optimal choice as an indicator to analyze which fuel option can more significantly change the composition of optimal choices when land-use efficiency changes by ±50%. The range of efficiency change tested in the sensitivity analysis is based on a survey of potential factors that may impact land-use intensity of examined fuel options (Table SP-1). At the county level, we inspected the optimal choice of which counties is more sensitive to land-use efficiency change. The counties that are more sensitive means that the land-use efficiency advantage of the optimal choice is limited and the competing fuel option should also be considered.

3. Results and discussion

3.1. Land-use intensity

County-level land-use intensities of each renewable fuel option are presented in Fig. 1a–g. Biodiesel produced from algae, solar electricity, and wind electricity clearly show lower land-use intensities than that of corn and switchgrass ethanol. In other words, these fuel options generally use land more efficiently and therefore need less land to fuel the same amount of VMT. Maps with scales specific to each fuel option are included in the Supplemental Information (Figure SI-1a–g).

Corn ethanol was the least land-efficient fuel choice on average. The land-use intensity of corn ethanol ranged from 0.14 to 7.33 m^2/VMT, with a weighted average of 0.56 m^2/VMT (weighted by area). Land-use efficiency tends to be higher in the Midwestern states and lowest in parts of Texas and Oklahoma. The gray color in Fig. 1a indicates areas where either corn is not grown or the data are proprietary (data not available in the USDA report). Comparing to the scenario using only corn starch for ethanol production, including corn stover as feedstock can increase corn ethanol land-use efficiency by 15% (in average) and up to 45%. Results for land-use intensity of corn starch ethanol are presented in the Supporting Information (Figure SI-2a and b).

In general, lowland switchgrass ethanol is more land efficient than upland switchgrass ethanol (Fig. 1b and c). The land-use intensity of lowland switchgrass ethanol ranged from 0.13 to 3.04 m^2/VMT, with a weighted average of 0.44 m^2/VMT. The land-use intensity of upland switchgrass ranged from 0.19 to 3.3 m^2/VMT, with a weighted average of 1.71 m^2/VMT. Both ecotypes are more land-efficient in the Eastern half of the country than in the Western half. The gray areas indicate regions that are not suitable for switchgrass ethanol.

The land-use intensity of biodiesel produced from open-system algae ranged from 0.1 to 0.37 m^2/VMT, with a weighted average of 0.2 m^2/VMT. Land efficiency is the highest in states along the Southern border of the country and lowest in parts of Montana, Idaho, Wyoming, Colorado, Maine, Minnesota, and Michigan (Figure SI-1d). Much of the Midwest and the northeast regions are not suitable in the near term for large-scale open-pond algae cultivation due to lower temperature, shorter growth season, and lower level of radiation (Wigmosta et al., 2011).

Biodiesel produced from closed-system algae tended to be more efficient than that of open-pond algae, with a land-use intensity range of 0.047–0.117 m^2/VMT, with a weighted average of 0.079 m^2/VMT. Land intensity values tended to be the lowest in states in the Southwestern region of the country and highest along the Great Lakes and in portions of Colorado and Washington (Figure SI-1e), also mainly due to the geological differences in solar radiation intensities. Open-pond algae are especially vulnerable to climate factors, with cold climate shortening growing season significantly.

In general, solar electricity is the most efficient fuel choice among alternative fuel options examined in this study. The land-use intensity of solar electricity ranged from 0.013 to 0.031 m^2/VMT, with a weighted average of 0.019 m^2/VMT. Values tended to be lower in the Southwestern portion of the country and highest in the Northwest and Northeast parts of the country (Figure Fig. SI-1f).

The land-use intensity of wind electricity ranged from 0.023 to 0.031 m^2/VMT, with a weighted average of 0.029 m^2/VMT. The most efficient regions are found in patches on the Western side of the country, including areas of California, Nevada, Utah, Colorado, Montana, Idaho, Wyoming and New Mexico. States in the middle of the country tend to have high values but high values were found in patches throughout all other parts of the country as well. The gray color on the wind map indicates areas that are not suitable for wind power (Figure SI-1g).

3.2. Optimal choice at the county scale

To identify land-efficient fuel options at the regional scale, we separate fuel options examined in this study into two groups: engineered systems (wind electricity, solar electricity, and biodiesel produced from closed-system algae) and natural systems (corn ethanol, switchgrass ethanol, and biodiesel produced from open-pond algae). Fuel options in the engineered system group collect energy through engineered products (e.g. solar panel, wind turbine, bioreactors), while those in the natural system group collect energy through cultivation. Engineered systems in general require less amount of land to produce the same amount of energy comparing to natural systems whose land-use efficiencies depend more on geographical locations and local land quality (e.g. soil quality).

For natural systems, biodiesel from open-system algae and lowland switchgrass ethanol are more land efficient than corn ethanol and upland switchgrass ethanol (Fig. 2a). Biodiesel from open-pond algae dominates the Western, Central, and Southern portions of the country, while lowland switchgrass ethanol dominates in the Midwest and Northeast. Corn ethanol and upland switchgrass ethanol are optimal in only a handful of counties. For engineered systems, solar is the most land-efficient option except in two counties in Washington (Fig. 2b).

3.3. Sensitivity of regional optimal choice

Sensitivity analysis was performed for each of the natural systems and engineered systems to determine to which fuel option the optimal choice is most sensitive. A percent increase in the land-use efficiency for each option represents a percent decrease in the amount of land needed to fuel one VMT (land intensity).

3.3.1. Natural systems

At the aggregated national level, the composition of optimal fuel choices is most sensitive to land-use efficiency of lowland switchgrass ethanol (both land-use efficiency improvement and efficiency decrease) and biodiesel from open-pond algae (efficiency reduction). Because corn ethanol is relatively less land-efficient and is only the optimal fuel option in very limited regions, further reduction of land-use efficiency does not impact overall optimal fuel choices while land-use efficiency improvement can increase the percentage of area having corn ethanol as the optimal choice slightly (Fig. 3a). The percentage of areas that has lowland switchgrass ethanol as the optimal fuel option increases or decreases linearly in response to land-use efficiency change of lowland switchgrass ethanol (Fig. 3b). Assuming the land-use efficiency of other fuel options stays the same, increasing land-use efficiency of lowland switchgrass ethanol increases the percentage of land having lowland switchgrass ethanol as the optimal choice and decreases that of biodiesel from open-pond algae. Similarly, decreasing land-use efficiency of lowland switchgrass ethanol (while assuming no change for other fuel options) decreases the percentage of land with lowland switchgrass ethanol as the optimal choice and increases that of biodiesel from open-pond algae. When all areas available for biodiesel from open-pond algae have biodiesel from open-pond algae as the optimal choice (option saturated), the percentage of land with upland switchgrass ethanol as the optimal starts to increase, while that of lowland switchgrass decreases. The percentage of land with upland switchgrass ethanol as the optimal choice only significantly increases when its

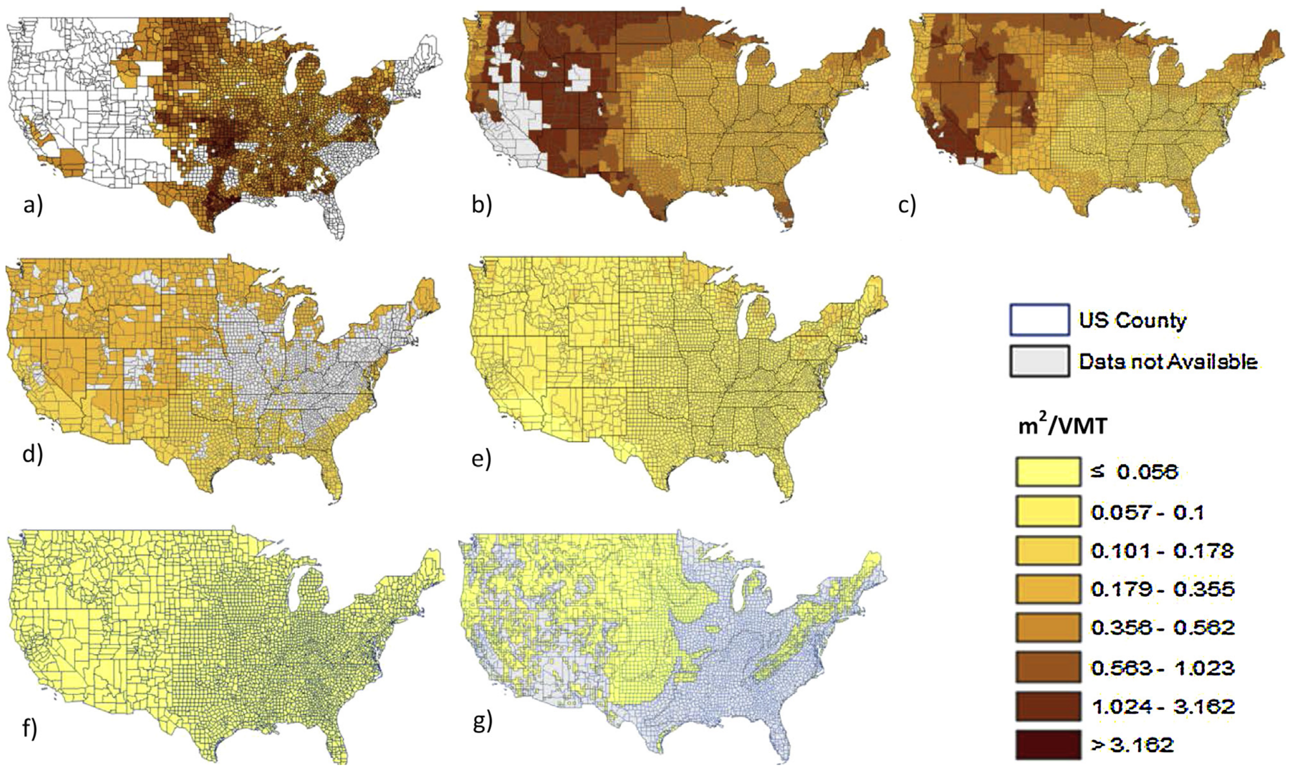

Fig. 1. Land-use intensity of different renewable fuel options. County-level land-use intensity measured in m^2/VMT for different renewable fuel options: (a) corn ethanol, (b) upland switchgrass ethanol, (c) lowland switchgrass ethanol, (d) biodiesel produced from open-system algae, (e) biodiesel produced from closed-system algae, (f) solar electricity, and (g) wind electricity. All maps are presented on the same scale. The gray color indicates areas where either the area is not suitable for the specific fuel option or data are not available. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

land-use efficiency is higher than that of lowland switchgrass ethanol (Fig. 3c). Land-use efficiency improvement of biodiesel from open-system algae only has limited effects in increasing the percentage of land with algae biodiesel as the optimal choice because of its unsuitability in certain regions (Figs. 1d and 3d). When the land-use efficiency of biodiesel from open-pond algae decreases, the area that has biodiesel from open-pond algae as the optimal choice gradually switches to favor lowland switchgrass ethanol (Fig. 3d).

In addition, we examined the geographic distribution of regions whose optimal fuel choice is sensitive to land-use efficiency increase (reduction of land-use intensity) of different fuel options. Efficiency improvement of lowland switchgrass ethanol will increase its favorability in Nebraska, eastern Colorado, New Mexico, northern Texas and Louisiana, southern Missouri, Alabama, and South Carolina, and western Washington and Oregon (Fig. 4a). Increasing land-use efficiency of upland switchgrass based ethanol enables it to be the optimal choice in the northeast and mid-west regions (Fig. 4b). However, at least 15% efficiency improvement of upland switchgrass ethanol is required in most regions. Only a handful of counties are sensitive to land-use efficiency improvement of corn ethanol (Fig. 4c), indicating large disparity of land-use efficiency of corn ethanol compared to other fuel options at the county level. Regions that are most sensitive to land-use efficiency improvement of biodiesel from open-pond algae are Oklahoma, Kansas, Arkansas, northern Missouri and Alabama, eastern North Carolina, and southern Nebraska (Fig. 4d). These are the regions with relatively lower algae productivity due to a combination of colder temperature, shorter growing seasons, and lower level of solar radiation.

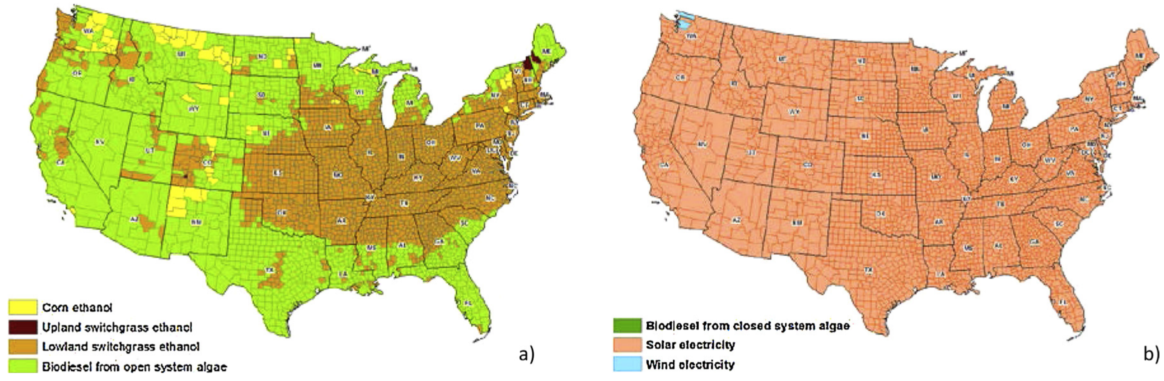

Fig. 2. Regional optimal renewable energy choices based on land-use intensity. (a) Natural systems. Land-use intensities in m^2/VMT were compared among corn ethanol, upland switchgrass ethanol, lowland switchgrass ethanol, and biodiesel produced from open-pond algae to determine the optimal fuel choice from the land-use perspective. (b) Engineered systems. Land-use intensities in m^2/VMT were compared among wind electricity, solar electricity, and biodiesel produced from closed-system algae to determine the optimal choice from the land-use perspective.

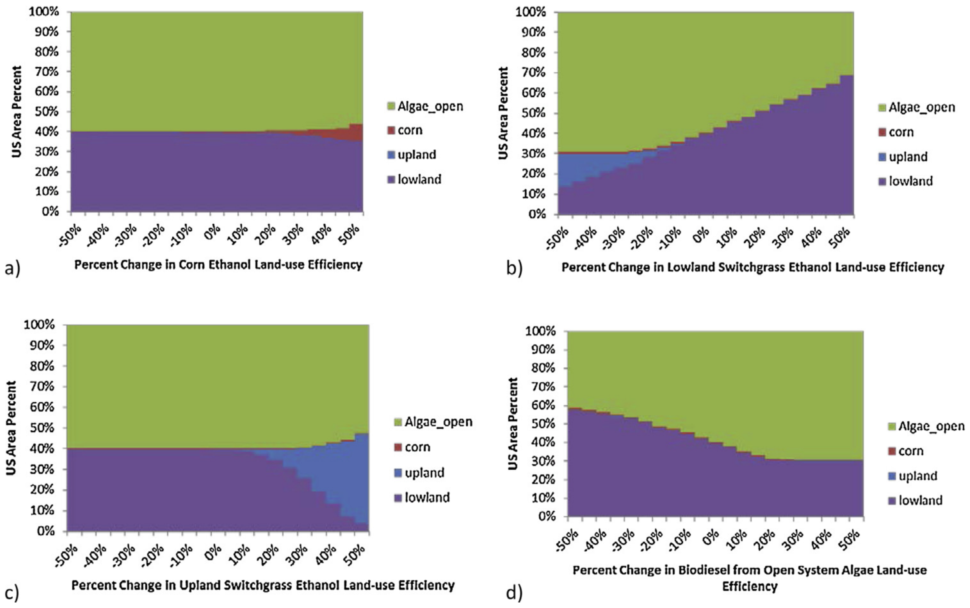

Fig. 3. Sensitivity analysis of regional optimal fuel choice for natural systems. Percentage of total area having different fuel options as the optimal fuel choice in reaction to land-use efficiency change of (a) corn ethanol, (b) lowland switchgrass ethanol, (c) upland switchgrass ethanol, and (d) biodiesel produced from open-pond algae.

3.3.2. *Engineered systems*

For the engineered systems, the optimal fuel choice is only sensitive to the land-use efficiency change of wind and solar electricity (Fig. 5a and b). These two options are in competition with each other and land efficiency improvement in one will cause the other one to be less favorable. Biodiesel produced from closed-system algae is not as competitive as wind and solar electricity from the land efficiency perspective.

Geographically, states in northern West and Midwest (Oregon, Idaho, Montana, North Dakota, etc.) are more sensitive to land-use efficiency improvement of wind electricity (Fig. 6). These results indicate that developing wind electricity for clean vehicle systems

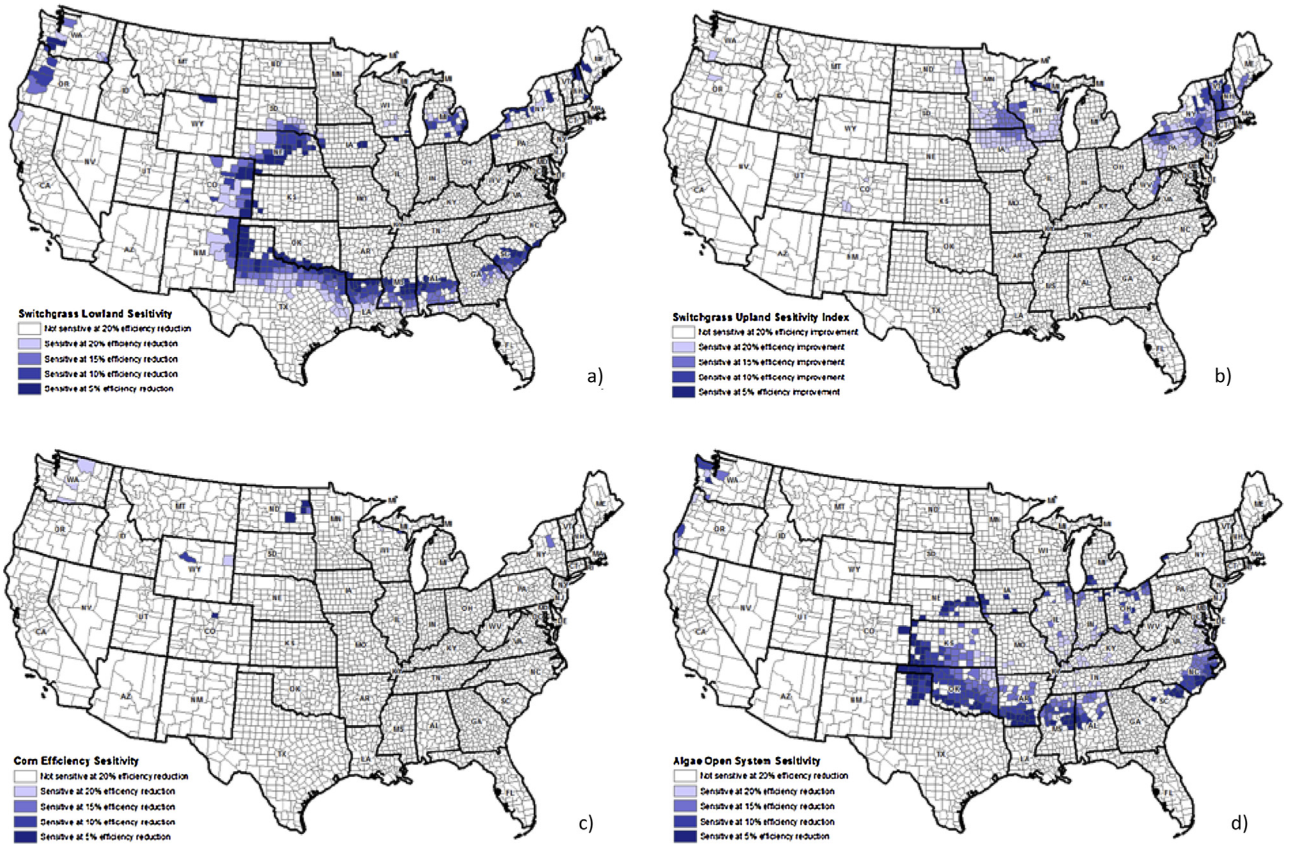

Fig. 4. Geographical sensitivity of the natural system optimal choice to land-use efficiency improvement of individual fuel option: (a) lowland switchgrass ethanol, (b) upland switchgrass ethanol, (c) corn ethanol, (d) biodiesel generated from open-pond algae. Darker color means higher sensitivity to land-use efficiency change (i.e. less efficiency improvement is required to change the regional optimal fuel choice from the land-use perspective).

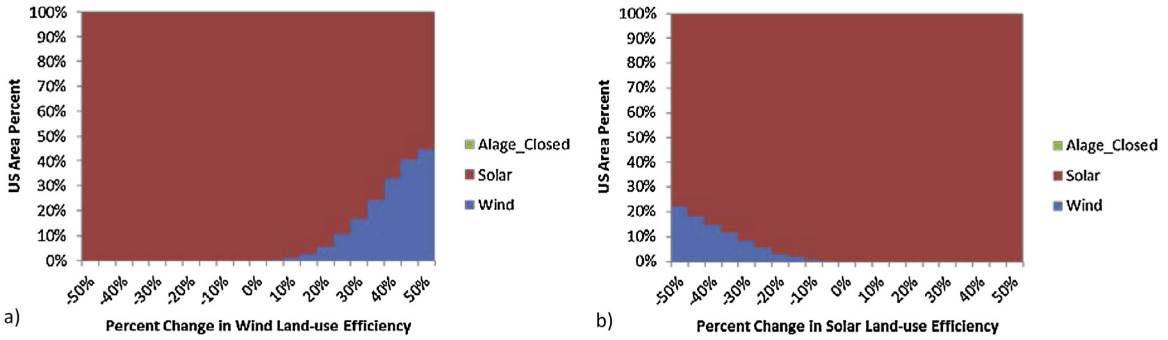

Fig. 5. Sensitivity analysis of engineered systems. Percentage of total area having different fuel options as the regional optimal fuel choice in reaction to land-use efficiency change of (a) wind electricity and (b) solar electricity.

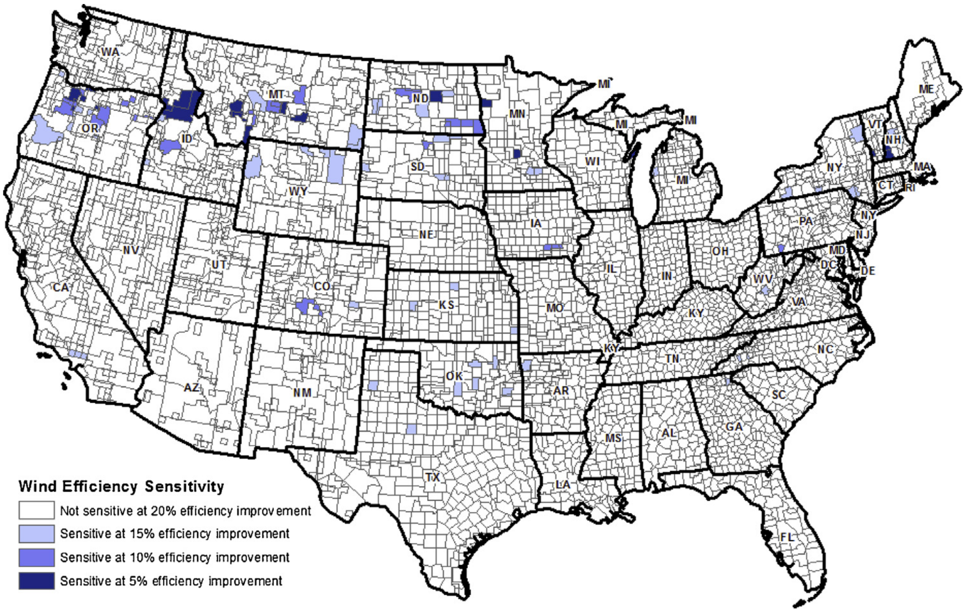

Fig. 6. Geographical sensitivity of engineered systems to land-use efficiency improvement of wind electricity.

in these regions can be land-efficient with reasonable technology improvement (e.g. 15% efficiency increase). An efficiency improvement of 20% for biodiesel produced from closed-system algae is not sufficient to make it the optimal choice in any county.

3.4. Limitations

This study demonstrates the need for considering regional fueling strategies to minimize the land-use impact of the emerging clean vehicle system. It has several limitations that can be improved in future studies. Firstly, this study limited each fuel option to one specific fuel type. For example, switchgrass is only analyzed for ethanol production while it can also be used to produce electricity (a.k.a. bioelectricity) (Campbell et al., 2009; Choudhary et al., 2014; Clarens et al., 2011) for electric vehicles. The “blend wall”, which is the maximum amount of ethanol that can be blended into gasoline for the use of existing fleet (Qiu et al., 2014; Strogen et al., 2012), of using ethanol as transportation fuel is not considered. Secondly, dual land-use is not considered in this study. In certain regions, wind energy production has the potential to be integrated with agriculture activities on farm and pasture land (Mulvaney et al., 2013). Such dual land-use can potentially reduce the land-use intensity of wind electricity and needs to further exploration. We also assume stationary solar panels for solar electricity. Tracking panels can increase the output by 12–45%, depending on the tracking panel being 1-axis or 2-axis and the geographic locations (Drury et al., 2014; Lave and Kleissl, 2011). However, a cost-benefit analysis will need to be conducted to evaluate the economic payoffs of installing more expensive tracking panels. In addition, the effects of indirect land-use change that occur from converting sensitive or otherwise valuable land for renewable fuel production are not included in this study. Future research could integrate land quantity and land quality in the analysis. Furthermore, economic viability of different fuel options at the regional scale should also be incorporated into future research. Lastly, this research is based on current technologies. High uncertainties exist for clean transportation fuel development. The change of yield due to climate change over time and the uncertainties of future technology development are also important to be addressed in future research.

4. Conclusions and policy implications

This study shows the importance of considering land-use efficiency of different renewable transportation fuels and regional variations when governments make decisions about developing a clean vehicle system. In general, fuel options from the engineered systems are more land efficient than those in natural systems; and solar photovoltaic electricity has the lowest land-use intensity among all options evaluated in this study, followed by wind electricity. For biofuels, algae biodiesel is more land efficient than corn and switchgrass ethanol. Depending on the geological location, different regional fueling strategies could result significantly different land-use demand to generate the same amount of energy. These results shed light on developing both federal and state level policies to minimize land-use impact for the development of the clean vehicle system.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2014.12.008.

References

Alternative Fuels Data Center. Fuel properties comparison. U.S Department of Energy – Energy Efficiency and Renewable Energy; 2012 www.afdc.energy.gov/fuels/fuel_properties.php

Arent DJ, Wise A, Gelman R. The status and prospects of renewable energy for combating global warming. Energy Econ 2011;33:584–93.

Black & Veatch Corporation. Cost and performance data for power generation technologies. Golden, CO: National Renewable Energy Laboratory; 2012.

Bureau of Transportation Statistics. Average fuel efficiency of U.S. light duty vehicles. Washington, DC: United States Department of Transportation; 2011.

Cai H, Hu X, Xu M. Impact of emerging clean vehicle system on water stress. Appl Energy 2013;111:644–51.

Campbell JE, Lobell DB, Field CB. Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science 2009;324:1055–7.

de Castro C, Mediavilla M, Miguel LJ, Frechoso F. Global solar electric potential: a review of their technical and sustainable limits. Renew Sustain Energy Rev 2013;28:824–35.

Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resour Conserv Recycl 2009;53: 434–47.

Chiu Y-W, Wu M. Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways. Environ Sci Technol 2012;46:9155–62.

Choudhary S, Liang S, Cai H, Keoleian G, Miller S, Kelly J, et al. Reference and functional unit can change bioenergy pathway choices. Int J Life Cycle Assess 2014;19:796–805.

Clarens AF, Nassau H, Resurreccion EP, White MA, Colosi LM. Environmental impacts of algae-derived biodiesel and bioelectricity for transportation. Environ Sci Technol 2011;45:7554–60.

Congress US. Energy Independence and Security Act of 2007; 2007.

Congressional Budget Office. Energy security in the United States. Congress of the United States; 2012.

Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power. Part II: Reliability, system and transmission costs, and policies. Energy Policy 2011;39:1170–90.

DOE US. New plug-in hybrids; 2013.

Drury E, Lopez A, Denholm P, Margolis R. Relative performance of tracking versus fixed tilt photovoltaic systems in the USA. Prog Photovolt Res Appl 2014;22:1302–15.

DSIRE. Database of State Incentives for Renewables and Efficiency; 2014.

Dunn J, Mueller S, Kwon H-y, Wang M. Land-use change and greenhouse gas emissions from corn and cellulosic ethanol. Biotechnol Biofuels 2013;6:51.

Elliott J, Sharma B, Best N, Glotter M, Dunn JB, Foster I, et al. A spatial modeling framework to evaluate domestic biofuel-induced potential land use changes and emissions. Environ Sci Technol 2014;48:2488–96.

EPA. EPA and NHTSA set standards to reduce greenhouse gases and improve fuel economy for model years 2017–2025 cars and light trucks. Regulatory Announcement. Office of Transportation and Air Quality; 2012.

Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M, et al. Methodology guidelines on life cycle assessment of photovoltaic electricity. 2nd ed.; 2011, St. Ursen, Switzerland.

Fthenakis V, Kim HC. Land use and electricity generation: a life-cycle analysis. Renew Sustain Energy Rev 2009;13:1465–74.

Geyer R, Stoms D, Kallaos J. Spatially-explicit life cycle assessment of sun-to-wheels transportation pathways in the US. Environ Sci Technol 2013;47:1170–6.

Gunderson CA, Davis EB, Jager H, West TO, Perlack RD, Brandt CC, et al. Exploring potential US switchgrass production for lignocellulosic ethanol. Oak Ridge, Tennessee: Oak Ridge National Laboratory; 2008.

Horner RM, Clark CE. Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. Renew Sustain Energy Rev 2013;23:129–37.

Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson CA, Wullschleger SD. Empirical geographic modeling of switchgrass yields in the United States. GCB Bioenergy 2010;2:248–57.

Kelly JC, MacDonald JS, Keoleian GA. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl Energy 2012;94:395–405.

Kim HC, Fthenakis V, Choi J-K, Turney DE. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation. J Ind Ecol 2012;16:S110–21.

Lambin EF, Meyfroidt P. Global land use change, economic globalization, and the looming land scarcity. Proc Natl Acad Sci 2011;108:3465–72.

Lave M, Kleissl J. Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental United States. Renew Energy 2011;36:1145–52.

Liska AJ, Yang H, Milner M, Goddard S, Blanco-Canqui H, Pelton MP, et al. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. Nat Clim Change 2014;4:398–401.

Lopez A, Roberts B, Heimiller D, Blair N, Porro G. US renewable energy technical potentials: a GIS-based analysis. Golden, CO: National Renewable Energy laboratory; 2012.

Masters GM. Renewable and efficient electric power systems. Hoboken, NJ: John Wiley & Sons Inc; 2004.

McDonald RI, Fargione J, Kiesecker J, Miller W, Powell J. Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America. PLoS ONE 2009;4:11.

Miller SA. Minimizing land use and nitrogen intensity of bioenergy. Environ Sci Technol 2010;44:3932–9.

Mulvaney KK, Woodson P, Prokopy LS. A tale of three counties: understanding wind development in the rural Midwestern United States. Energy Policy 2013;56:322–30.

NREL. State clean energy practices: renewable fuel standards. NREL Technical Report NREL/TP-640-41075 NREL/TP-670-43513; 2008.

NREL. Wind data. National Renewable Energy Laboratory; 2011.

NREL. Photovoltaic solar resource of the United States; 2012.

Oak Ridge National Laboratory. US billion-ton update: biomass supply for a bioenergy and bioproducts industry; 2011.

Phillips BR, Middleton RS. SimWIND: a geospatial infrastructure model for optimizing wind power generation and transmission. Energy Policy 2012;43:291–302.

Pioneer Agronomy Sciences. Sustainable corn stover harvest for biofuel production. Crop Focus 2011.

Qiu C, Colson G, Wetzstein M. An ethanol blend wall shift is prone to increase petroleum gasoline demand. Energy Econ 2014;44:160–5.

Quinn JC, Catton K, Wagner N, Bradley TH. Current large-scale US biofuel potential from microalgae cultivated in photobioreactors. Bioenergy Res 2012;5:49–60.

Rathmann R, Szklo A, Schaeffer R. Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Renew Energy 2010;35:14–22.

Sarkar S, Miller SA. Water quality impacts of converting intensively-managed agricultural lands to switchgrass. Biomass Bioenergy 2014;68:32–43.

Schnepf R, Yacobucci BD. Congressional Research Service, editor. Renewable fuel standard (RFS): overview and issues. Darby, PA: Diane Publishing; 2010.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 2008;319:1238–40.

Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, et al. Energy and environmental aspects of using corn stover for fuel ethanol. J Ind Ecol 2003;7:117–46.

Spatari S, Zhang Y, MacLean HL. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. Environ Sci Technol 2005;39:9750–8.

Strogen B, Horvath A, McKone TE. Fuel miles and the blend wall: costs and emissions from ethanol distribution in the United States. Environ Sci Technol 2012;46:5285–93.

Thomson AM, Izarrualde RC, West TO, Parrish DJ, Tyler DD, Williams JR. Simulating potential switchgrass production in the United States. Richland, WA: Pacific Northwest National Laboratory; 2009.

Tulbure MG, Wimberly MC, Boe A, Owens VN. Climatic and genetic controls of yields of switchgrass, a model bioenergy species. Agric Ecosyst Environ 2012;146:121–9.

U.S. Department of Energy EIA. Annual energy review, Table 4-4. Washington, DC; 2013a.

U.S. Department of Energy EIA. Monthly energy review. Washington, DC; 2013b.

U.S. EPA. Inventory of U.S. greenhouse gas emissions and sinks, 1990–2011; 2013.

United States Department of Agriculture. National Agricultural Statistics Service, editor. U.S. corn yields by county; 2011, Washington, DC.

Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P. Food vs. fuel: the use of land for lignocellulosic ‘next generation’ energy crops that minimize competition with primary food production. GCB Bioenergy 2012;4:1–19.

Wang MQ, Han J, Haq Z, Tyner WE, Wu M, Elgowainy A. Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. Biomass Bioenergy 2011;35:1885–96.

Wigmosta MS, Coleman AM, Skaggs RJ, Huesemann MH, Lane LJ. National microalgae biofuel production potential and resource demand. Water Resour Res 2011;47:13.