Land use carbon implications of a reduction in ethanol production and an increase in well-managed pastures

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Background: As the debate over governmental subsidization of ethanol continues, the academic and policy communities should prepare for a potential reduction of ethanol production, and be aware of the potential land use impacts. We report a first-order estimate of carbon implications of the change in land use that results from a reduction of ethanol production from current levels and having well-managed pasture as an alternative land management option. **Method:** An integrated biogeophysical–socioeconomic model is used to evaluate three levels of potential reductions in ethanol production, along with the possibility of conversion of cropland to pasture management. **Results:** Results indicate that up to 10 million ha of cropland could be converted to pastureland, reducing agricultural land use emissions by nearly 10 teragrams carbon equivalent per year, a 36% decline in carbon emissions from agricultural land use.

Over the past 10 years, commodity grain prices have doubled, reaching their highest levels in over 30 years [101]. The rise in prices culminated in the food price spikes of 2008 and 2011, where food riots erupted in 40 countries. Although the relative increase in food prices in the USA was less severe than in poorer nations, the impact of the price spikes has caused outcry from interests as diverse as the animal feedlot industry and the food security community. From 2007 to 2011, meat, milk and egg prices in the USA have increased by over 20% and livestock feed costs have risen by 30% [1]. The number of Americans participating in the Supplemental Nutrition Assistance Program has increased by 69%, from 26.3 million in 2006 to 44.6 million in 2011. Individual benefits are tied to the food price index; therefore, increases in food prices have contributed to Supplemental Nutrition Assistance Program governmental costs swelling to US$60 billion per year [2,102].

Although studies have pointed to a number of factors leading to the increased food prices, the ethanol industry, whether deservingly or not, is seen as the major factor behind the price spikes [3,4]. Several recent studies have contributed to the poor public opinion of ethanol by concluding that ethanol is neither a net energy source nor a net reducer of carbon emissions [5,6]. The impact of these research reports combined with recent spikes in commodity prices has led to fierce political efforts to reduce or eliminate subsidies for ethanol [7,8]. Opponents of ethanol subsidization won a significant battle with Congress recently, voting to eliminate federal blender's tax credits and ethanol import tariffs [9]. Ethanol proponents have defended continued subsidization of corn grain ethanol as a way to support the biofuel industry until lignocellulosic **second-generation biofuels** can be developed. Lignocellulosic ethanol relies on woody, nonfood feedstocks, which are considered to have better net energy returns than first-generation corn-grain ethanol. If second-generation biofuels can be developed, they would simultaneously contribute to both offsetting dependence on foreign oil and reducing carbon levels. Yet technical hurdles have stagnated development of second-generation biofuels, forcing the US EPA to reduce the mandated quantities set out in the 2007 expansion of the Renewable Fuels Standard for the second year in a row [10]. A recent analysis of ongoing efforts to produce second-generation fuels concludes that the industry will fail to contribute substantially to

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Key terms

Second-generation biofuels: Biofuels made from woody or cellulosic material, which is still under development and relies on complex enzymes or gasification technology.

First-generation biofuels: Biofuels such as corn grain ethanol, which rely on longstanding fermentation technology.

Carbon sequestration: Process of removing carbon from the atmosphere and storing it in a reservoir, such as the soil, where it will not reenter the atmosphere.

Management-intensive grazing: Method of rotational grazing using relatively high stock densities, daily to weekly livestock moves and long rest periods for paddock recovery.

Well-managed pastures: Pastures composed of high-yielding pasture species, usually maintained in a vegetative state.

the EPA's Renewable Fuel Standard targets even by 2022 [11]. If another sharp spike in commodity prices occurs in the near future, some have speculated that ethanol production mandates could be scaled back or eliminated [103]. In the span of less than 3 years the expected role of ethanol in the agricultural sector has gone from one of rapid growth and longevity, to one of which the societal benefits and technical feasibility are being strongly questioned.

In light of the rapidly changing expectations regarding the future of ethanol, we believe it is an appropriate time to evaluate the land use and carbon implications of a possible scaling down of ethanol production. Several studies have investigated the land use implications of the growth of the biofuels industry [12–14], but there have been none to date that have investigated the implications of a drawdown of **first-generation biofuels** and the non-emergence of second-generation biofuels. In this analysis, we investigate such a future scenario and the potential of permanent managed pasture as an alternative land use that could provide carbon benefits.

Although grazing systems have long been associated with land degradation in the arid and semi-arid west, new management approaches utilizing some form of rotational grazing are believed to reverse degradation and potentially lead to soil and pasture improvement if well managed, with implications for soil carbon storage.

The primary management practices associated with improved soil **carbon sequestration** in pastures are nutrient management and grazing methods. **Management-intensive grazing** (MIG), also known as intensive rotational grazing or prescribed grazing, is one such practice increasingly recognized for its ability to improve environmental quality in permanent pastures. MIG is a technique involving short-duration (1–6 days), high stock density grazing and long rest periods [15–17]. MIG promotes better pasture utilization [18] and allows pastures to recuperate after each grazing event, which is thought to 'pulse' carbon into the soil via root sloughing [19,20]. Paddock rotation, along with balancing cool and warm season grasses and legumes, has been shown under some circumstances to enable ranchers to increase stocking rates while simultaneously increasing soil organic carbon (SOC) relative to continuous grazing [21]. The adoption of MIG has been primarily producer led, although evidence of economic benefits to dairy producers in particular [22–24] has resulted in increased acceptance among state-level extension agencies in eastern and midwestern USA dairy regions. A recent survey found that 13% of dairies in Maryland, Pennsylvania, New York and Vermont are using MIG [25]. Various US Department of Agriculture (USDA) programs to promote conservation of, or conversion to, permanent pasture or grassland, exist primarily based on the value of decreasing the potential for soil erosion as well as improving water quality [26]. Among beef producers in the western rangelands, MIG is more controversial [27] and for the purposes of this study, our focus is on the rain-fed grazing land east of the 100th parallel in North America.

The carbon offset potential of well-managed permanent pasture has been estimated to be quite large. Globally, non-economic evaluation estimates that 150 teragrams carbon per year ($\mathrm{TgCyr^{-1}}$) could be sequestered in pasturelands [28]. Within Annex I nations, it is estimated that 70 $\mathrm{TgCyr^{-1}}$ could be sequestered in pasturelands [21]. Empirical studies within the USA have estimated that sequestration rates for **well-managed pastures** range from 0.21 to 2.9 megagrams of carbon per hectare per year ($\mathrm{MgCha^{-1}yr^{-1}}$) [21,26,29,30]. Thus, if the 55 million ha of pastureland and rangeland in non-arid regions of the USA was converted to well-managed permanent pasture, carbon sequestration could reach 12–160 $\mathrm{TgCyr^{-1}}$, potentially offsetting 1–10% of total US GHG emissions. Conversion of cropland to well-managed pastures, which is the focus of this study, would increase these potential offsets. This is a broad range of potential and further empirical analysis is needed.

Our objective in this article is to evaluate the potential conversion of cropland into pastureland induced by a reduction of ethanol production, and the resulting implications upon soil carbon and emissions from input use. As nonprofitable cropland is converted to pastureland, it is expected that carbon emissions associated with crop production inputs will decline and soil carbon will increase. This is necessarily a first-order assessment, as it does not consider that a decrease in the price of corn will simultaneously impact feed cost for the confinement livestock sector, which has implications for the demand curve for pasture-raised beef production.

Methodology

The analytical tool used to conduct this analysis is an integrated socioeconomic–biogeophysical model. The integrated model is driven by data on economics, soil attributes, crop rotation, land management and energy consumption. The economic core of the model is a modified version of the University of Tennessee's Policy Analysis System model (POLYSYS), which is a partial equilibrium displacement model that iterates annually and simulates results until the year 2030 [31–33]. All policy scenarios are analyzed in comparison with the USDA 'business as usual' baseline projections for the crop and livestock sectors. POLYSYS has been used to estimate carbon offset credit supply potential for conservation tillage and herbaceous grasses used for bioenergy [14,34].

POLYSYS is structured as a system of interdependent modules simulating: crop supply for the continental USA, which is disaggregated into 3110 production regions; national crop demands and prices; national livestock supply and demand; and agricultural income. Variables that drive the modules include planted and harvested area, production inputs, yield, exports, costs of production, demand by use, farm price, government program outlays and net realized income. Management practices currently considered in POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, hay, herbaceous and woody cellulosic feedstocks, afforestation and pastureland. Three levels of tillage management are included for each crop. Conventional tillage, reduced tillage and conservation tillage are defined, respectively, as leaving less than 15% of the ground covered by crop residue, between 15 and 30% ground cover, and greater than 30% ground cover [35]. Baseline increases in no-tillage adoption were extended through to 2030 by projecting state-level tillage trends reported by the Conservation Tillage Information Center at a conservative 50% rate. Changes in tillage mix away from the baseline are determined by relative changes in profitability in alternative scenarios.

The model makes use of over 3500 unique regional crop budgets, which are based on regional differences in crop production operations. These 'operation budgets' list a daily schedule of all machinery and production inputs used to produce each crop. Both direct and indirect energy and carbon emissions have been tied to each input of the operation budgets [36]. 'Direct carbon' includes emissions from the use of fuel on farms, dissolution of agricultural lime, changes in soil carbon and carbon equivalent (C_{eq}) emissions of N_2O. Carbon content of diesel was estimated at 0.81 kg l^{-1} diesel. Emissions of N_2O resulting from the application of nitrogen fertilizer were estimated according to IPCC guidelines [37] and as outlined by Marland *et al.* [38]. C_{eq} emissions of N_2O from the use of nitrogen fertilizers are estimated using 2.22 tons C_{eq} released per ton of nitrogen applied. Emissions from lime is 0.06 ton of carbon per ton of limestone applied. 'Indirect carbon' includes CO_2 emissions from fossil fuels used in the production, transport and application of all agricultural inputs have been calculated by West and Marland for cultivated lands [39]. By tying emissions to operations and inputs applied, the model can estimate changes in production emissions under assumptions of land use changes.

Several layers of biogeophysical data were integrated to develop a model capable of estimating changes in SOC at the county level. Regional carbon management response curves [40], State Soil Geographic Database (STATSGO) soils data [41] and Landsat land cover data [42] were integrated to determine potential changes in SOC associated with each unique combination of soil type, crop type and crop management [43]. The amounts of carbon that could be sequestered under land management practices, such as conservation tillage or pasture conversion, were based on regionally unique soil conditions and previous land use. Experimental data on the carbon changes under conservation tillage, herbaceous grasses and afforestation to the 30 cm depth were collected and integrated into the model as detailed in earlier studies [14,34,43]. Because a significant amount of cropland is already using conservation tillage, there is a baseline level of carbon sequestration already occurring.

Policy-induced changes in land use result in estimated changes in crop production emissions, soil carbon sequestration and net carbon flux to the atmosphere from agricultural activity. Net carbon flux includes changes in soil carbon stocks, and both direct and indirect emissions from the manufacture and use of all crop production inputs. The current study does not account for CH_4 or N_2O emissions from livestock.

Cropland can be converted between major crop types as the relative profitability of one crop overreaches another. Cropland can also be converted to pastureland if the economic profit of all major crop management practices become negative for 3 consecutive years and all fixed capital equity is eroded. At this point, pastureland, which is assumed to return a normal economic profit, becomes a viable economic land use option. Carbon emissions associated with planting and establishing permanent pasture grasses are estimated using the same methodology as other management practices. We assume pasture renovation once every 10 years, with moderate nitrogen and lime applications at seeding but no additional applications. We assume that cropland converted to pastureland east to the 100th meridian can sequester carbon. Soil dynamics on more arid western lands are more controversial, so our estimates exclude any sequestration on converted lands west of the 100th meridian [27]. Converted eastern cropland under pasture management accumulates soil carbon at a rate of 1.85% of the initial regional soil carbon level per year [44]. This rate does not represent some extreme regional weather or soil conditions, but is only used to estimate mean conditions. Nationally, soil carbon sequestration averages to 0.41 $MgCha^{-1}yr^{-1}$, which is similar to empirical estimates of carbon accumulation under well-managed pastures [21].

We analyze three scenarios of ethanol drawdown and compare them with the extended USDA baseline scenario, where corn ethanol production reaches 15 billion gallons by 2020 and then remains constant through 2030. To fully investigate the carbon potential of pasture management, this analysis assumes an exogenous drawdown level of ethanol demand. The three alternative scenarios slowly reduce ethanol production annually until reduced by a total of 25, 50 or 100% by 2025, where production remains steady through to 2030. An alternative would be to allow ethanol to compete with gasoline under an unmandated marketplace. We chose not to do this for two reasons: future price of competing gasoline is uncertain, and ethanol may be forcibly shut down due to a food price spike event and concern over energy and carbon balances. By exogenously setting the drawdown levels, we can give perspective of the range of future possibilities. The results will list ethanol production costs per unit for each scenario for comparison with current gasoline production costs. Future scenarios could endogenously link ethanol demand to energy and feedstock prices.

The economic model solves both crop and livestock markets simultaneously; therefore, as commodity prices decline the livestock market responds by demanding more feed for feedlots. Our first-order analysis does not consider the supply of cattle raised upon converted cropland or the tradeoffs that may occur between feedlot finishing and pasture finishing. Although we discuss the potential implications of the increased livestock supply and potential pasture finishing in the discussion, the implicit effects could be integrated into future analyses. Our analysis is also limited to conversion of cropland to improved pasture management and does not consider management improvements that may occur on already existing pasturelands.

Results

In the 2030 baseline scenario year, major crop agriculture in the USA emits 39 TgC_{eq} from production inputs and sequesters 12 TgC in the soils of 68 million ha under conservation tillage, to result in a net flux of 27 TgC_{eq} from US agricultural land use to the atmosphere [36,43]. As ethanol production is scaled down, corn production for ethanol feedstocks decline and prices fall. Year 2020 corn prices decline from $4.20 per bushel to $2.50 per bushel in the 100% drawdown scenario. Declining corn prices induce conversion of corn cropland to other major crops, which in turn reduces other crop prices as supply is increased. In regions where declining crop prices lead to no crop being a profitable alternative, cropland is converted to pasture management. The majority of the converting land was previously growing corn, but some land from other crops also converts as commodity prices decline across all crops. In the 100% drawdown scenario, 10.3 million ha of cropland is estimated to convert to pastureland by 2030. Some amount of cropland is converted to pasture in most regions of the country, but the majority of new pasturelands convert from previous cornland in the heart of the cornbelt, concentrating on Ohio, Illinois, Iowa, Nebraska and Minnesota (Figure 1).

The new land use equilibrium induced by ethanol drawdown has a different pattern of crop input use than the baseline scenario. Corn production is input intensive, so in most regions land use movement away from corn and into other crops or pasture management results in a net decline in input use (Figure 2A). Nationally, production input emissions decline by 5.74 TgC_{eq} in the 100% drawdown scenario.

The new land use equilibrium also has a different pattern of soil carbon sequestration than the baseline situation. Well-managed pasture sequesters carbon at a rate higher than annual crop agriculture; therefore, large regional conversion to pasture results in net increases in sequestration of carbon (Figure 2B). Yet in some regions, if there is conversion from no-tillage to more intensive tillage crops, then a net loss of soil carbon can occur. In our model scenarios, we assume cropland converted to pasture in western lands does not sequester carbon; therefore, a transition from no-tillage cropland to pasture results in a net decrease in soil carbon accumulation. This could occur in situations where the lost cropland has a high net primary productivity (NPP) due to irrigation and the newly converted pasture has a low NPP due to dryland management methods. In Figure 2B, losses in soil carbon are most concentrated in western areas and gains in soil carbon occur in eastern areas where we are assuming increased SOC under well-managed pasture.

When both changes in carbon associated with production inputs and changes in soil carbon accumulation are summed, net carbon flux from agricultural land use to the atmosphere can be estimated. In most regions net flux is reduced by both a decline in input emissions and uptake of carbon by soils. Large regional reductions in net flux to the atmosphere occur throughout the cornbelt (Figure 2C). In regions where carbon uptake declined, the impact of lost carbon accumulation is often offset by larger reductions in emissions associated with input use. In very few regions, the 100% drawdown scenario resulted in a net flux increase.

Nationally, net carbon flux from agricultural land use declines as ethanol drawdown occurs (Figure 3). Approximately half of the reductions in net flux are from reductions in input use (-5.74 TgC_{eq}) and half are from increases soil carbon uptake (-4.17 TgC_{eq}). Having well-managed pastures as a viable economic alternative to crop agriculture results in a 9, 19 and 36% decline

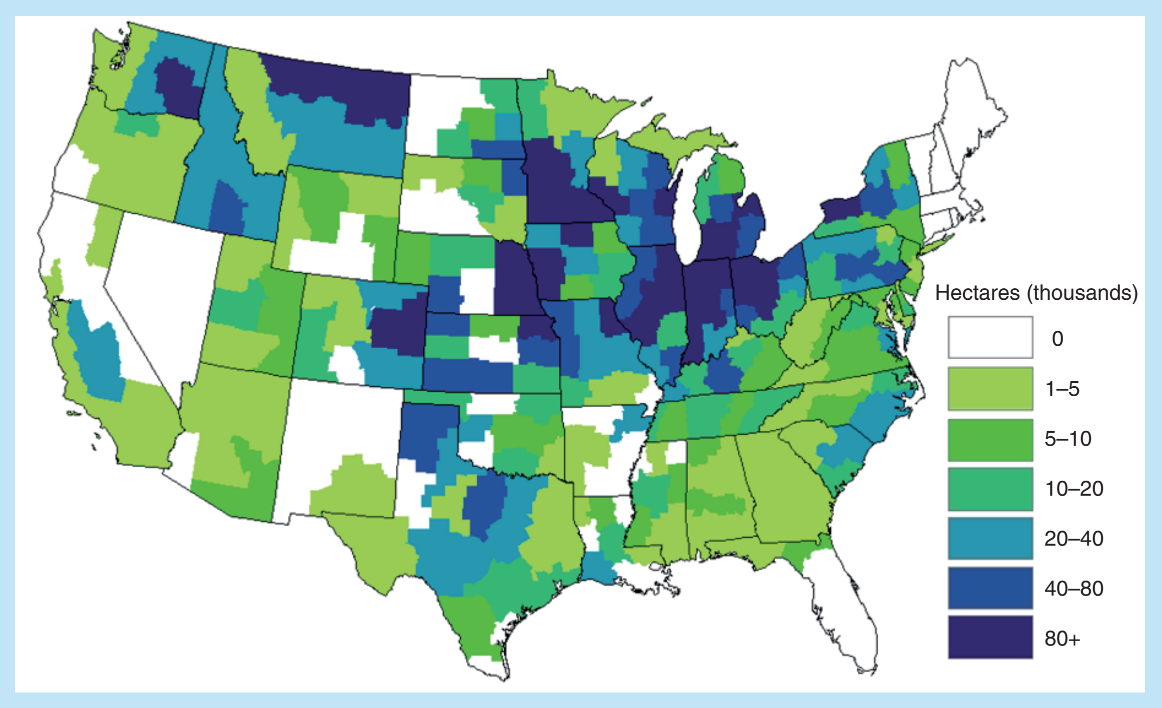

Figure 1. Land converted from crop agriculture to pasture management as a result of a 100% drawdown in corn grain ethanol demand by 2030. Shown as total hectares converted per Agricultural Statistic District.

in total net carbon flux from land use agriculture under 25, 50 and 100% ethanol production drawdown, respectively (Table 1). Soil carbon increase can occur for 20–30 years [37], after which a steady state of SOC is reached in the soil, and no additional accumulations can occur. Therefore annual net flux reductions will eventually fall to only the reductions brought about by decreased input use.

Ethanol production costs decrease as drawdown levels increase due to declines in corn grain feedstock cost (Table 2). When comparing year 2030 ethanol energy equivalent production costs with current gasoline production costs, ethanol is competitive with gasoline in all drawdown scenarios except the baseline scenario. This indicates that under an unsubsidized and unmandated marketplace, ethanol would likely be produced at quantities above the 25% drawdown level. The ethanol drawdown levels analyzed in this paper would therefore have to be caused by other movements, such as political action in response to food security issues induced by food price spike events or concern over net energy and carbon balances. In the current food and policy environment, action beyond removal of mandates is not unquestionable, hence the rationale for investigating the larger drawdown scenario. For example the 100% drawdown would not likely occur without legislative action to forbid production, or an unforeseen decline in oil prices or oil demand.

Discussion

The results of our analysis indicate that if policy changes and technical infeasibility alter the expected production path of ethanol in the USA, conversion of nonprofitable agricultural lands to pastures can lead to significant reductions in land use carbon emissions. This result is significant in that it indicates that positive movement, in terms of carbon emissions, can occur even in the event of a drawdown or dissolution of the biofuel industry. Yet the potential carbon benefits of pastureland conversion will only occur if croplands converted to 'well-managed' pastures, which accumulate soil carbon, are not associated with severe increases in N_2O or CH_4 emissions and are profitable for producers. We will discuss these three critical issues below.

▪ Soil carbon sequestration under permanent pasture/MIG

It is reasonably well established that grazing has a positive impact on soil carbon sequestration [45–48]. Studies using exclosures indicate that a change in plant species composition may be partially responsible for the increased carbon accumulation under grazing relative to nongrazed grasslands, but positive feedbacks to herbivory may influence belowground carbon fate [49], and much remains to be understood regarding the mechanisms responsible [50]. Nonetheless, soil carbon sequestration rates are directly related to NPP [44,51]. Thus,

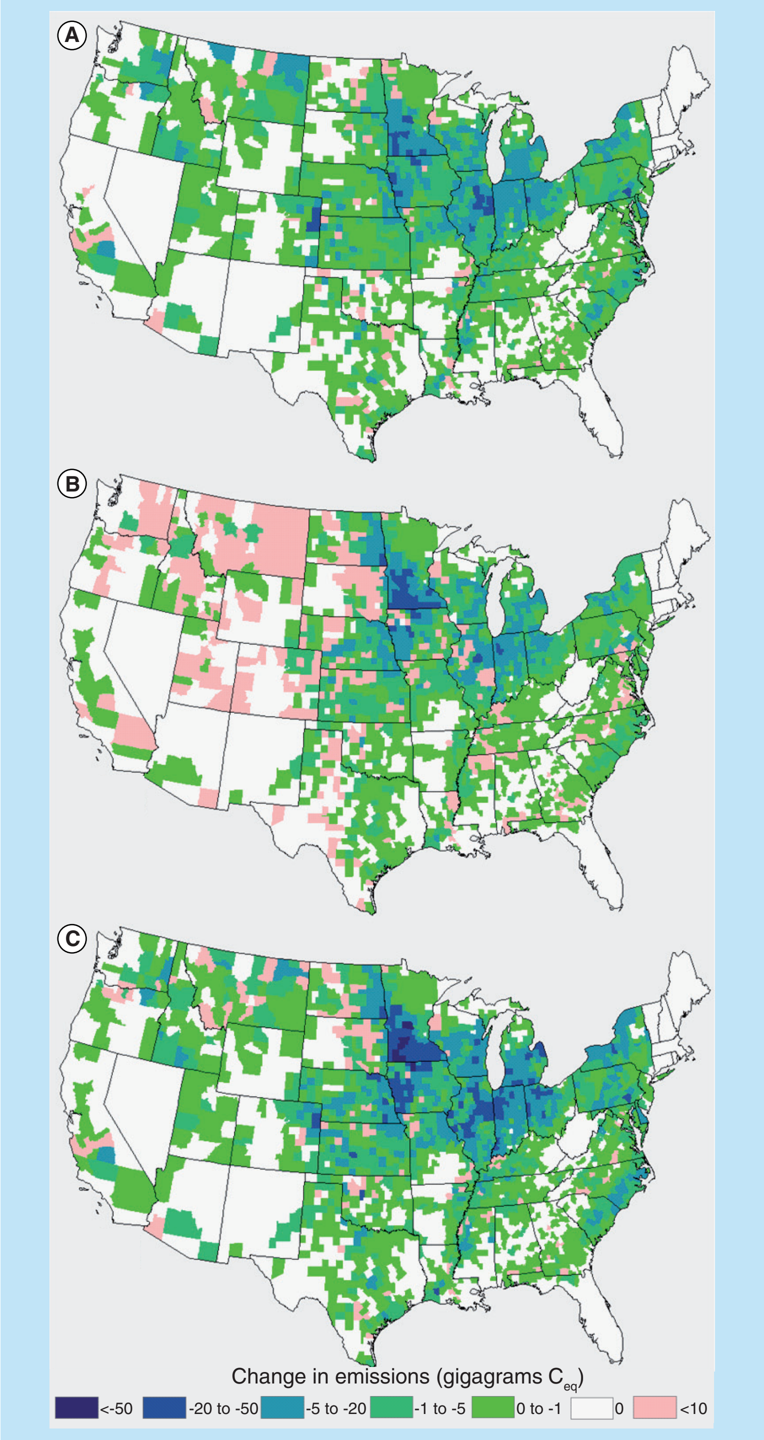

Figure 2. County level changes in emissions from agricultural land use to the atmosphere in 2030 as a result of a 100% reduction in ethanol production. (A) Indicates the change in emissions from production input use, **(B)** indicates the change in emissions from soil carbon and **(C)** indicates the net flux from both input use and soil carbon. Positive numbers (pink) indicate a net release of carbon to the atmosphere and negative numbers (green and blue) indicate a net reduction in emissions to the atmosphere relative to the baseline scenario.

in order to maximize carbon storage under managed pasture, management for high NPP is necessary.

In the beef industry, cow/calf and stocker segments may not warrant as high a level of management of pasture as finishing beef cows on grass for grass-fed markets or dairy, both of which require high quality grass and high levels of intake to achieve desired product quality. Under our scenario of land conversion, additional supply of pasture implies greater supply of pastured livestock. It is unlikely that this pasture would be utilized entirely by cow/calf producers as this is only one piece of the beef supply chain and is currently close to equilibrium with the demand for feeder calves. Thus, we necessarily imply an increase in pastured stockers and finishing beef, displacing some of the livestock currently grown out in concentrated animal feeding operations. An associated implication is that some portion of the 'new' permanent pasture would likely be managed for high quality and NPP, with a high likelihood of the use of MIG.

Some empirical evidence exists in support of the positive role of MIG in pasture productivity relative to continuously grazed pastures. Teague *et al.* investigated paired pastures in three counties in a tallgrass prairie region of north central Texas, comparing light (14 animal units [AU] 100 ha^{-1}) and heavy (27 AU 100 ha^{-1}) stocking rates grazed continuously to pastures using MIG (27 AU 100 ha^{-1}), and found standing biomass at peak standing crop to be highest on the MIG system (3960 [light stocking], 2696 [light stocking] and 4680 [MIG] Kg ha^{-1}) [52]. Older work found higher stocking rate and productivity under six- and 11-paddock rotations compared with continuous grazing in Illinois [53]. Phillip *et al.* found a strong interaction between stocking rate and rotational frequency, with the highest system efficiency using a moderate (6-day) rotation compared with a more intensive frequency of 2 days, with most of the benefit coming from the ability to hay early season growth compared with continuous grazing [54]. However, the impact of MIG on soil carbon sequestration may be a function of soil processes beyond simple productivity [18,52], and some evidence has been found that MIG promotes soil carbon storage.

Little work has been done to investigate soil carbon sequestration under pastures managed with MIG. Conant *et al.* sampled soils under pastures in Virginia paired by grazing method and estimated total soil carbon to be 22% greater under MIG than in neighboring extensively grazed or hayed pastures [21]. Averaging across their four sites, they found a storage rate of 0.41 MgCha^{-1}yr^{-1} using MIG. Teague *et al.* found a 44% increase in soil organic matter under pastures managed with MIG for 9 years compared with heavy continuous grazing and 11% increase compared with

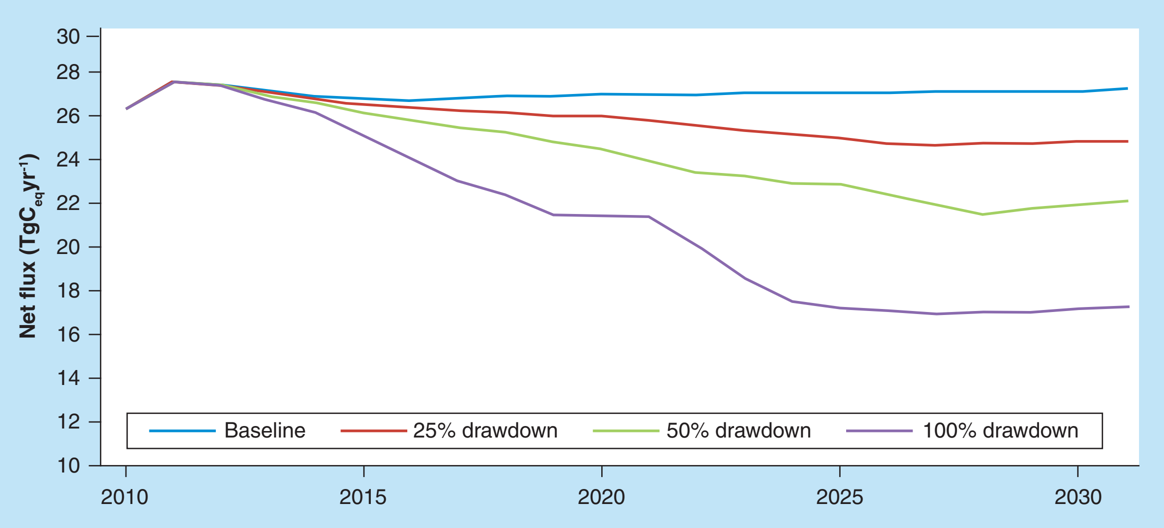

Figure 3. Net flux of carbon from agricultural land use to the atmosphere under baseline and three levels of ethanol production drawdown, with well-managed pasture as a viable economic alternative to crop agriculture. In all three scenarios, the percent drawdown occurs steadily from 2010 through to 2025 and then remains constant. As land use adjusts to new economic circumstances, reductions in input use and increases in soil carbon uptake result in reductions to net flux.

$TgC_{eq}yr^{-1}$: Teragrams carbon equivalent per year.

light grazing [52]. They did not estimate a storage rate for soil carbon using MIG. The rate of soil carbon accumulation used in this analysis approximately equals the estimate of Conant *et al.* of 0.41 $MgCha^{-1}yr^{-1}$ [21]. In their work, one site was estimated to sequester soil carbon at 2.9 $MgCha^{-1}yr^{-1}$. They note the inherent difficulty in measuring soil carbon storage rates due to spatial variability across sites and soils. Given the low number of studies reporting soil carbon sequestration under MIG, much work remains to be done. To date, there have been no randomized, replicated studies under controlled experimental conditions on MIG. However, as a pasture management approach, MIG holds promise to increase soil carbon while providing an economically and environmentally beneficial livestock system.

▪ Full accounting for GHG emissions from grazing

As has been pointed out by others [55,56], the full impact of land conversion to grazing on net GHG emissions needs to consider additional GHGs. One option for managing pastures for high productivity is by increasing nitrogen supply. This can be achieved through additions of synthetic nitrogen fertilizer, manure or by increasing the percentage of legumes in the pasture. All three

Table 1. Cropland converted to well-managed pasture and associated annual emissions of carbon from agricultural land use to the atmosphere in 2030 under three scenarios of corn ethanol drawdown[†].

Scenario	Baseline	Reduction in corn ethanol		
		25%	50%	100%
Corn acreage (M ha)	37.5	35.3	32.6	27.2
Pasture conversion (M ha)	0.0	2.0	5.2	10.3
Emissions from agriculture to the atmosphere (TgC_{eq})[‡]:				
▪ From production inputs	39.41	38.01	36.47	33.67
▪ From soils	-12.21	-13.17	-14.36	-16.38
▪ Net flux	27.2	24.84	22.11	17.29
Change in net flux from baseline (TgC_{eq})		-2.36	-5.09	-9.91
Change in net flux from baseline (%)		-9	-19	-36

[†] The authors assume cropland converted to pastureland east of the 100th meridian sequesters carbon at a rate of 1.85% of initial soil carbon per year, which averages to 0.41 $MgCha^{-1}yr^{-1}$. The authors also assume no carbon accumulation on cropland converted to pastureland west of the 100th meridian.

[‡] Positive numbers indicate a carbon release from agriculture to the atmosphere; negative numbers indicate a carbon capture from the atmosphere to the soil.

MgC: Megagrams carbon; M ha: Million hectares; TgC_{eq}: Teragrams carbon equivalent.

Table 2. Corn grain price and ethanol production costs in gasoline energy equivalent terms in 2030 under baseline and three scenarios of corn ethanol drawdown[†].

Scenario	Baseline	Reduction in corn ethanol		
		25%	50%	100%
Corn grain price (US$ Mt^{-1})	152.86	129.64	122.14	109.29
Ethanol production cost in gasoline energy equivalents (US$ l^{-1}):				
▪ Feedstock cost	0.65	0.55	0.52	0.47
▪ Conversion cost	0.23	0.23	0.23	0.23
▪ Distillers grains income	0.13	0.11	0.10	0.09
Total cost (US$)	0.75	0.67	0.65	0.60

[†]Ethanol costs are listed as the production costs to displace the energy equivalent of one gallon of gasoline. The authors assume gasoline has 1.56-times the energy content of ethanol. For comparative purposes, the August 2011 gasoline production cost was US$0.73 per l.

nitrogen sources have implications for N_2O emissions and are therefore of concern, given the much higher greenhouse warming potential of N_2O compared with CO_2, and could potentially negate the value of the carbon sink created. However, emissions associated with synthetic nitrogen application are generally higher than manure nitrogen sources and much higher than legume nitrogen sources [57]. Our model assumes pasture renovation once every 10 years, with moderate nitrogen and lime applications at seeding but no additional applications. Depending on other factors controlling production potential, such as climate and soil type, some strategic use of nitrogen fertilizer may be possible while still achieving the emissions and sequestration goals [57]. Grazing practices may have a larger impact on overall productivity, but also carry implications for controlling N_2O emissions. There is some evidence that grazing can reduce pasture N_2O emissions relative to nongrazed grasslands [58]; however, net emissions will depend on management.

Conventionally, continuous grazing, whereby livestock are allowed to move freely through the whole grazing area for a season, has been the standard practice, but is increasingly being implicated in pasture degradation and, more recently, in increased N_2O emissions from livestock operations. N_2O emissions are exacerbated when soil compaction occurs, which is a particular problem near permanent water and mineral points in a continuously grazed pasture, or where animals 'camp out' under shade [59]. Rotational grazing helps to mitigate this problem because water and minerals move with the animals from paddock to paddock. Under MIG, where animals are kept in small paddocks but moved as frequently as daily, animal impact is evenly distributed throughout the land, and pastures are allowed to recover for weeks to months before livestock return. Thus, compaction and continuous loading of manure onto specific areas is avoided, decreasing conditions conducive to N_2O emissions.

With respect to CH_4, it is known that enteric CH_4 emissions are generally higher in grass-fed ruminants than animals consuming grain, as a result of the differences in metabolizable energy intake [60]. Although soil-dwelling methanotrophs consume soil-generated CH_4 in pastures, uptake rates are far too low to fully compensate for the amount of CH_4 that would be released from enteric fermentation at normal stocking rates [61]. Thus, a full accounting for CH_4 emissions in a pasture-based livestock system would need to be included in estimates of net emissions.

Allard *et al.* measured CO_2, N_2O and CH_4 emissions from pastures managed intensively (high stocking rate and nitrogen fertilizer applied) and extensively (low stocking rate and no nitrogen fertilizer) and found both to be significant net C_{eq} sinks, with the intensively managed pasture exceeding the extensively managed pasture [62]. Recent modeling work by Rotz *et al.*, performing full life cycle analysis comparing dairy management systems, estimated that a 60-cow dairy would reduce its net life cycle GHG emissions by 10–22%, by switching from a confinement model to a pasture-based system, depending on assumptions regarding soil carbon sequestration rates [60]. Although our analysis only determines net emissions from land use, these studies suggest that a major shift in the livestock industry toward increased use of pasture and away from grain feeding in confinement may help reduce net emission from the livestock sector.

▪ Economic viability

The emergence and growth of well-managed pasture techniques has come about only recently. Several case study analyses have concluded that well-managed pasture systems can be profitable [23,54,63,64]. Although these studies indicate that producers are receiving more than a normal profit margin, we used the conservative assumption that well-managed pastures return zero economic profit, and cropland only converts if there is no alternative profitable crop for multiple years. By looking strictly at economic criteria, well-managed pasture techniques appear well positioned to become more widespread under the scenarios evaluated in this analysis.

Yet, due to the recent advancement of well-managed pasture techniques, the major barrier to adoption may not be lack of economic returns, but lack of information – farmers have not grown up with the knowledge of intensive grazing techniques and agricultural extension services have been slow to prioritize intensive pasture management as an applicable practice for their regional livestock farmers. Therefore, knowledge barriers may hinder widespread adoption due to a lack of widely disseminated information on how to initiate improved pasture management techniques. If ethanol drawdown begins with no other active efforts toward promoting well-managed pastures, widespread adoption may not necessarily follow.

Due to the potential environmental benefits of widespread adoption of well-managed pastures, we propose that the following steps be taken to facilitate sound growth of the practices:

- Undertake empirical analyses of pasture systems to further quantify the carbon balances and identify key practices that maximize the carbon benefits;
- Educate farmers on key pasture management practices through farmer-to-farmer education programs facilitated through the US Cooperative Extension Service;
- Increase the economic viability of well-managed pastures through offering incentives tied to the soil carbon sequestration ability of pasture practices.

These steps will ensure that appropriate land use options are in place in the event that the ethanol industry experiences a drawdown. Likewise, facilitating sound growth in well-managed pasture techniques would also be beneficial if successful development of second-generation biofuels occurs. Previous studies analyzing land use change as a result of rapid growth of cellulosic feedstocks indicate that pasture improvements will be necessary to offset increased competition for grasslands [65].

Future perspective

As the debate over governmental subsidization of ethanol continues, the academic and policy communities should prepare for a potential reduction of ethanol production and be aware of the potential land use impacts. Agriculture faces many challenges in the near future. Climate change impacts combined with increasing fuel costs translate into a high likelihood that agriculture has entered a new period of history [66]. We could be transitioning from a 40-year period of commodity oversupply where prices have been below the cost of production, to a period of scarcity marked by high commodity prices. Ethanol may face continued difficulties from political pressure to reduce nonfood uses of our agricultural resources. If another food price spike occurs in the near future, ethanol mandates will very likely be curtailed or eliminated, with an all-out ban on ethanol being less likely, but still possible.

Executive summary

Ethanol situation

- Ethanol subsidies have recently been eliminated.
- Development of second-generation biofuels is lagging behind mandates.
- There is some political will to also eliminate ethanol mandates.
- High food prices are bringing ‘food versus fuel’ issues to the forefront and turning political will against ethanol.
- Corn grain ethanol may experience a production drawdown in the near future, with implications to feedstock demand and agricultural land use.

Alternative land use

- Improved pasture management is an alternative food use for land and has multiple environmental benefits, such as carbon sequestration, reduced erosion and reduced input use.
- Management-intensive grazing has been estimated to sequester from 0.21 to as high as 2.9 megagrams carbon equivalent per hectare per year.
- To date, adoption of management-intensive grazing has been farmer led.

Land use carbon potential of transition

- First-order analysis indicates that 10 million ha of cropland could convert to well-managed pastures by 2030 if ethanol experiences a 100% drawdown.
- Under 100% drawdown of ethanol, carbon emissions from agricultural land use would decline by 5.74 teragrams carbon equivalent per year and soils would absorb an additional 4.17 teragrams carbon equivalent per year.

Preparing for possible transition

- More empirical data needs to be collected on the most beneficial techniques in pasture management and their carbon sequestration potentials.
- To spur widespread adoption, farmer-to-farmer education programs would help overcome the barrier of lack of traditional knowledge on well-managed pasture techniques.
- Any future climate change programs should target the soil carbon benefits of well-managed pastures.

We report a first-order estimate of the land use carbon implications of a reduction of ethanol production and having well-managed pasture as an alternative management option. If ethanol production is completely eliminated over the next 20 years, well-managed pastures could potentially offset 10 TgC_{eq} from the atmosphere through both reducing land under input-intensive crop agriculture and by increasing soil carbon levels on the newly established pastures. At ethanol drawdown levels less than 100%, conversion to well-managed pastures can still make significant contributions to reducing the net flux of carbon from agriculture. Further empirical studies should continue to investigate the soil carbon, N_2O, and CH_4 implications of improved pasture systems, such as MIG, in relation to conventional pasture and feedlot systems for livestock production.

Due to the rapid emergence of new pasture management techniques, lack of a traditional knowledge base could be the major barrier to widespread adoption. We propose that the US Cooperative Extension Service facilitate farmer-to-farmer education programs to help disseminate information to farmers interested in alternatives to crop agriculture or conventional pasture management. Conversion would also be facilitated through farms employing well-managed pasture systems receiving incentives for increases in soil carbon stocks under possible future climate programs.

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