TRANSITION TO A BIO ECONOMY

Environmental and Rural Development Impacts

Proceedings of the October 15 and 16, 2008 Conference,
St. Louis, Missouri

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The conference was a collaboration of Farm Foundation, USDA Office of Energy Policy and New Uses, USDA Economic Research Service, USDA Rural Development, USDA Natural Resources Conservation Service, and the U.S. Forest Service.

Impacts of Land Conversion for Biofuel Cropping on Soil Organic Matter and Greenhouse Gas Emissions

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Abstract: To assess the value of biofuels, the environmental costs of their production must be compared with the benefits of displacing fossil fuel. This article focuses on the environmental impacts of biofuel cropping systems and calculates net greenhouse gas (GHG) emissions using life cycle analysis. The impacts of corn and switchgrass cropping for ethanol production were calculated for three states in the US (Iowa, Illinois, and Indiana) assuming three previous land use scenarios: Conservation Reserve Program (CRP) land, pasture land, and land already used for cropping. Although the results were different for the 3 states considered, the impacts of previous land use and cropping system were more important than location. Conversion of CRP lands to corn ethanol production would result in little net GHG savings compared to burning fossil fuel, greatly increase NO_3 leaching, and constrain other benefits of CRP land such as wildlife habitat. Conversion of pasture and crop land to corn ethanol cropping show GHG benefits, reductions in leaching for previously cropped systems, and increases in leaching for lands previously in pasture. Converting CRP land to switchgrass cropping would lessen the rate at which these soils store SOC, increase N_2O emissions, and have little impact on NO_3 leaching. Converting pasture and crop land to switchgrass cropping would increase SOC storage, decrease N_2O emissions, and decrease NO_3 leaching. We conclude that current land management (cropping system, tillage intensity, and fertilizer application), as well as previous land use, must both be considered to quantify the environmental impacts of biofuel cropping systems.

Biofuels are a growing alternative energy source, but there are environmental impacts associated with growing and processing biomass for fuel production. Impacts include greenhouse gas emissions (GHG), nitrogen oxides, and ammonia (NH_3) emissions, and nitrate (NO_3) leaching, The sources of these impacts can be placed into four categories; 1) producing and transporting farm inputs (fertilizers, pesticides, etc.), 2) operating farm equipment (tractors, harvesters, etc.), 3) cropping soils used to produce biomass, and 4) transporting and refining biomass to fuel. In this article we emphasize the impacts of biofuel production on soil carbon (C) and nitrogen (N) fluxes, but also perform complete life cycle analyses for GHG emissions in Iowa from all four sources, as well as account for the GHG benefits from displacing fossil fuel combustion.

Converting land to biofuel production affects soil organic matter levels, nitrogen (N) gas emissions, and NO_3 loss rates. Plowing soils typically leads to loss of C and N stored in soil organic matter. As soil organic matter decreases, GHG emissions tend to increase while soil fertility decreases. N additions from fertilizer increase N gas emissions and NO_3 leaching. Important N gases emitted from soils are nitrous oxide

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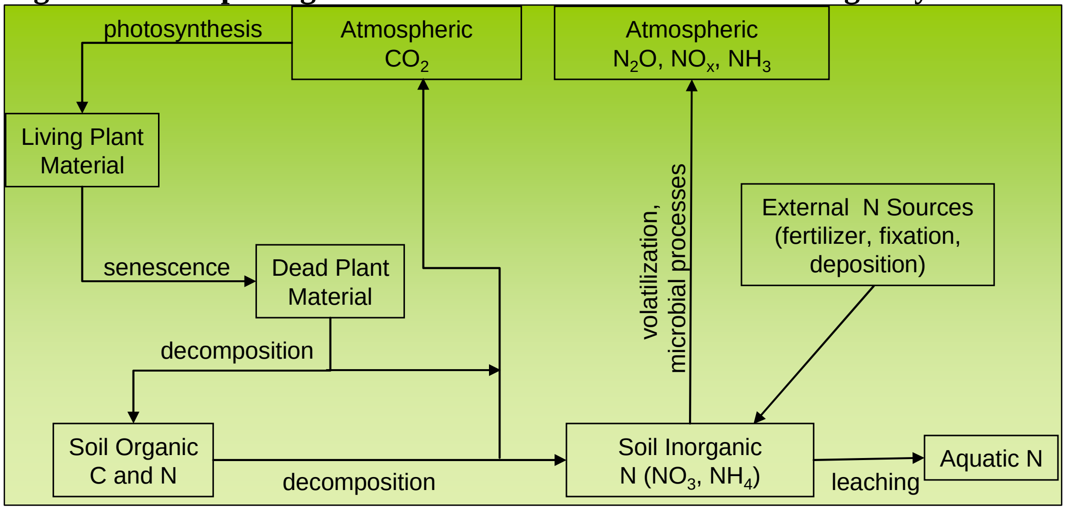
(N_2O), nitric oxide and nitrogen dioxide (NO_x), and ammonia (NH_3). N_2O is a potent GHG that also affects stratospheric ozone levels and agricultural soils are the primary anthropogenic source. NO_x is a source of ground-level ozone and contributes to acid rain. NH_3 also contributes to acid rain and eutrophication.

Soils are both a source and a sink of atmospheric carbon dioxide (CO_2) (Figure 1). CO_2 fixed from photosynthesis is transferred to surface litter pools when leaves and other above ground plant components die (i.e. senesce) and to soil litter pools when roots senesce or secrete chemicals (i.e., root exudation). Decomposition of litter returns CO_2 to the atmosphere but a portion of the C in litter remains on the soil surface and in soil organic matter. If C inputs from senesced vegetation and root exudation exceed carbon losses from decomposition of litter and soil organic matter, then soils are a net CO_2 sink. But if gaseous C losses exceed inputs, then soil becomes a net source of atmospheric CO_2. Factors influencing soil C balance include previous and current land use, soil properties such as texture, and weather.

Figure 1. Concept diagram of the terrestrial carbon and nitrogen cycles



In addition to C, soils are also a source and sink of N (Figure 1). Plant residues contribute organic N to soil litter pools which is converted to the inorganic form during decomposition. But, as with soil C, a portion of the N remains in soil organic matter. Besides decomposition, inorganic N can be added to soils via fertilizer/manure amendments, biological fixation, and atmospheric deposition of N compounds. N can be lost from soils in gaseous form and can be leached into groundwater or lost via overland water flow. The major pathways for gaseous N losses from soils are ammonia volatilization and microbial processes.

Nitrification and denitrification are two of the most important processes that contribute to N losses from soils (Firestone and Davidson, 1989). Nitrification is the aerobic oxidation of ammonium (NH_4) to NO_3. A portion of the transformed N is lost as N_2O and NO_x. Once N is in the NO_3 form, it is vulnerable to leaching because NO_3 is more soluble than NH_4, and can also be denitrified. Denitrification occurs when oxygen is limited and anaerobic microbes use NO_3 as an electron acceptor, resulting in the reduction of NO_3 to N_2O and N_2. As with soil C fluxes, land use practices, soil physical properties, and weather interact to control soil N losses. In particular, N gas emissions and NO_3 leaching tend to be correlated with external N inputs from fertilizer and organic matter additions, as well as N fixation from legume cropping.

The Energy Independence and Security Act of 2007 (EISA) mandates that 36 billion gallons of biofuel be produced in the US by 2022. For comparison, about 7 billion gallons of biofuel (ethanol plus biodiesel) were produced in 2007 in the US. To address the GHG emissions associated with biofuel production discussed above, the 2007 Energy Bill includes standards such that total emissions from grain-based ethanol must be at least 20% lower than using fossil fuel to generate an equivalent energy yield, grain-based biodiesel emissions must be at least 50% lower, and cellulosic-based fuel emissions at least 60% lower.

Our objectives were to investigate how current and previous land uses interact to control net GHG emissions and NO_3 leaching for different biofuel cropping systems in Iowa, Indiana, and Illinois. Approximately 40% of the corn used to produce ethanol in the US is expected to be grown in these states by 2010 according to Forest and Agricultural Sector Optimization Model (FASOM) projections (McCarl, 2008).

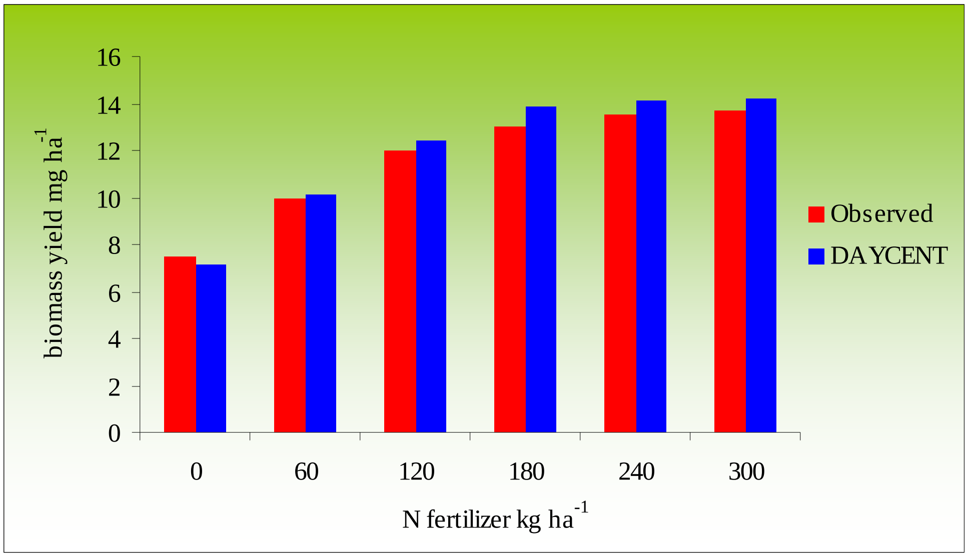
2. Methods

Soil Emissions and Crop Yields

The DAYCENT ecosystem model was used to estimate soil C and N losses from gaseous emissions and NO_3 leaching, as well as biomass yields. Daycent (Del Grosso et al., 2001; Parton et al., 1998) is a process-based model of intermediate complexity. DAYCENT simulates exchanges of carbon, nutrients, and trace gases among the atmosphere, soil, and plants as well as events and management practices such as fire, grazing, cultivation, and organic matter or fertilizer additions. To run DAYCENT for a particular site, soil texture, current and historical land use, and daily maximum/minimum temperature and precipitation data are required. DAYCENT includes submodels for plant growth and senescence of biomass; microbial decomposition of dead plant material and soil organic matter; water, nutrient and temperature flows through soil; evaporation and transpiration of soil water; and other processes. DAYCENT was selected by the EPA (EPA, 2008) to quantify N_2O emissions from major cropped and grazed systems in the US because model results generally compare favorably with measurements (Del Grosso et al., 2005) and the inputs required to run the model (weather, soil type, crop management, soil class) are available nationwide for the vast majority of agricultural land in the US.

The ability of DAYCENT to simulate grain yields form annual crops such as corn, wheat, and soybean has been previously confirmed (Del Grosso et al., 2005) but model generated yields for perennial biofuel crops, such as switchgrass, have only recently been validated. The current version of DAYCENT was tested using biomass yield data collected during two growing seasons near Ames, IA, from switchgrass plots receiving 6 levels of N fertilizer addition (Vogel et al., 2002). Both the DAYCENT model and observations showed a strong yields response as N increased up to 120 kg per ha but little response above 180 kg per ha (Figure 2).

Figure 2. Observed and DAYCENT simulated switchgrass biomass yields from plots near Ames, IA



GHG Life Cycle Analysis

As mentioned above, the DAYCENT model was used to estimate soil CO_2 and N gas emissions as well as NO_3 leaching losses. To fully account for soil N_2O emissions, direct, as well as indirect, N_2O emissions were considered. Direct N_2O is emitted from soil during nitrification and denitrification. Indirect N_2O results from the transformation of N that left the farm in a form other than N_2O. There are two pathways that produce indirect N_2O Emissions: 1) Volatilized N in the form of NO_x or NH_3 that is deposited and converted to N_2O off-site and 2) NO_3 leached into waterways that is converted to N_2O via aquatic denitrification. To estimate indirect N_2O, we used the default IPCC (2006) emission factors and assumed that 1% of volatilized N and 0.75% of leached NO_3-N are converted to N_2O. To convert total N_2O emissions to CO_2 equivalents we used a global warming potential of 310 (Forster et al., 2007). CO_2 emissions from fossil fuel used to manufacture and transport farm inputs were from West and Marland (2002), emissions from farm machinery operation were estimated using the IFSM model (Rotz, 2004), emissions from converting feedstock to ethanol (including transportation of biomass) and avoided emissions from displaced fossil fuel were calculated from crop yields and Sheehan et al. (2004), and avoided CO_2 emissions from co-products of biomass conversion were based on Ferrell et al. (2006). To summarize, total greenhouse gas emission calculations included 8 components: soil CO_2, direct soil N_2O, indirect soil N_2O, farm inputs, farm operations, feedstock conversion, displaced fossil fuel, and co-products.

Scenarios Simulated

We considered three previous land uses before conversion to biofuel cropping: existing cropping (i.e., 2 year corn/soybean rotation), Conservation Reserve Program (CRP), and pasture. The biofuel cropping systems considered were corn ethanol and switchgrass. To simulate corn ethanol we assumed a 5 year rotation with 4 years of corn followed by 1 year of soybean. N additions to corn, based on state averages, were 171, 162, and 144 kg per ha in IL, IN, and IA, respectively. N additions for switchgrass were 66, 63, and 56 kg per ha in IL, IN, and IA, respectively. Soybeans received no N fertilizer. Weather and soils data for each state were from randomly selected agricultural counties. Corn grain was harvested but no residue was removed and 85% of above ground biomass was harvested for switchgrass. We assumed reduced tillage cultivation. Land use conversion was assumed to occur in 2007 and results are presented as 10-year annual means for 2007-2016.

3. Results

Productivity, Soil GHG Fluxes, and NO_3 Leaching

Above ground net primary productivity (ANPP) was highest for corn/soy cropping, intermediate for pasture, and lowest for CRP (Figure 3a). Conversion to corn ethanol increased ANPP for all previous land uses (Figure 3b-d), even cropping, because soybeans were only grown once every 5 years in the corn ethanol rotation compared to every other year with the corn/soybean rotation, and corn produces more biomass than soybeans.

Figure 3. Above ground net primary productivity (ANPP) for crop (corn/soybean), pasture, and CRP lands in three states (a) and ANPP for land converted from crop, pasture, and CRP to corn ethanol and switchgrass in Iowa (b), Indiana (c) and Illinois (d). Results are 10-year means

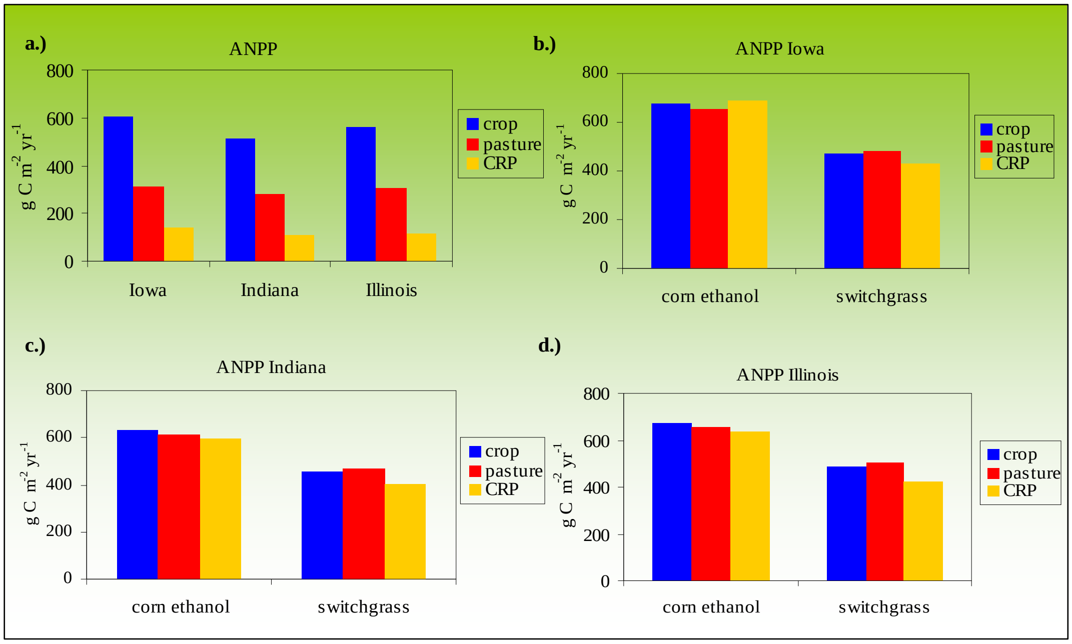
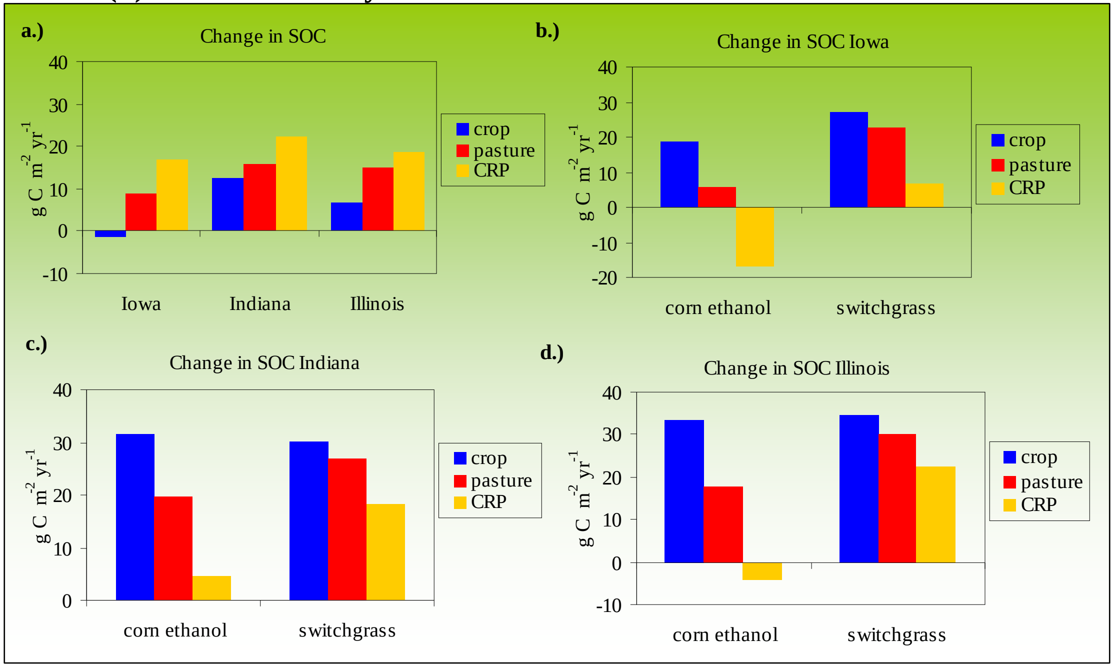


Figure 4. Changes in soil organic carbon (SOC) for crop (corn/soybean), pasture, and CRP lands in three states (a) and SOC changes for land converted from crop, pasture, and CRP to corn ethanol and switchgrass in Iowa (b), Indiana (c), and Illinois (d). Results are 10-year means.



Conversion to switchgrass reduced ANPP for croplands, but increased for pasture and CRP (Figure 3b-d), likely a result of switchgrass having lower N inputs than corn/soybean cropping, but higher N inputs than pasture or CRP. Soil organic carbon changes are close to neutral for corn/soy cropland in Iowa and positive for Indiana and Illinois, while pasture and CRP land stored soil organic carbon (SOC) in all 3 states (Figure 4a). Converting cropland or pasture to corn ethanol or switchgrass cropping led to gains in SOC, but converting CRP land to corn ethanol resulted in SOC losses in Iowa and Illinois (Figure 4b-d). N_2O emissions are highest for corn/soy cropping, intermediate for pastures, and lowest for CRP lands (Figure 5a). Conversion to corn ethanol cropping had little impact on N_2O emissions for land already cropped, but resulted in increased emissions for land that was previously in pasture or CRP (Figures 5b-d). Conversion of cropland and pasture to switchgrass decreased N_2O emissions but conversion from CRP to switchgrass increased N_2O (Figures 5b-d). Similar to N_2O, NO_3 leached was highest for corn/soy cropping, intermediate for pastures, and lowest for CRP lands (Figure 6a) and conversion to corn ethanol cropping had little impact for land already cropped, but resulted in increased leaching for land that was previously in pasture or CRP (Figures 6b-d). Conversion of cropland and pasture to switch grass decreased leaching but conversion from CRP to switchgrass increased leaching (Figures 6b-d). NO_3 leached tended to be higher if the previous land use was pasture and lower if the previous land was CRP upon conversion to corn ethanol, but previous land use has little impact if land was converted to switchgrass.

Figure 5. N_2O emissions for crop (corn/soybean), pasture, and CRP lands in three states (a) and emissions for land converted from crop, pasture, and CRP to corn ethanol and switchgrass in Iowa (b), Indiana (c), and Illinois (d). Results are 10-year means.

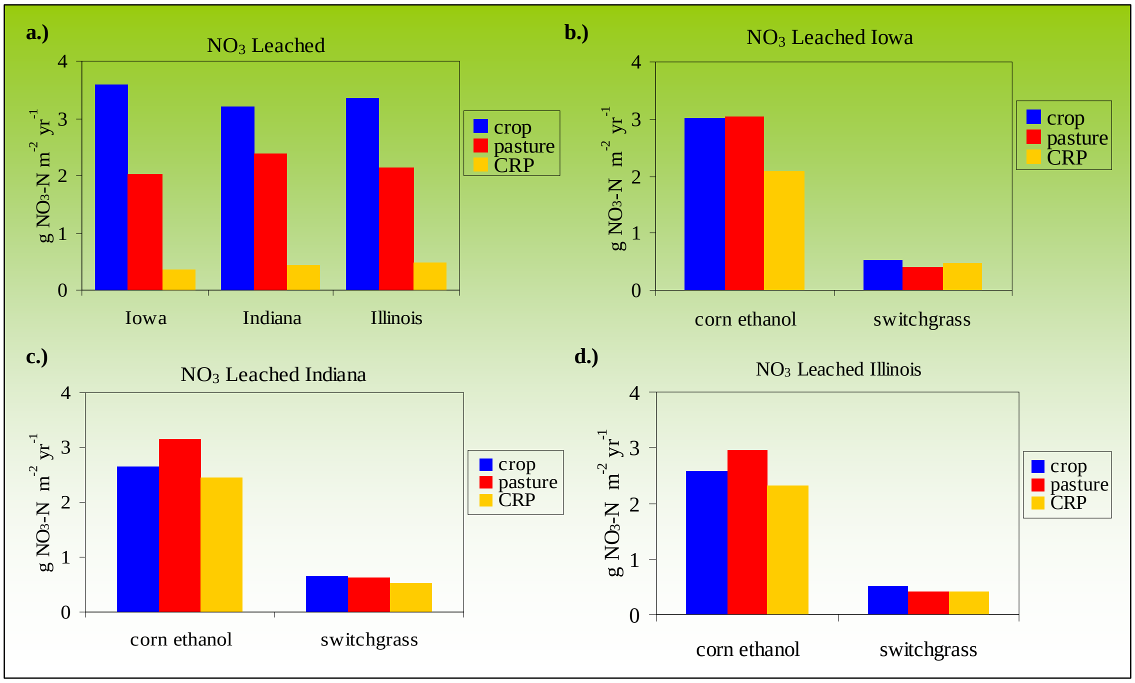
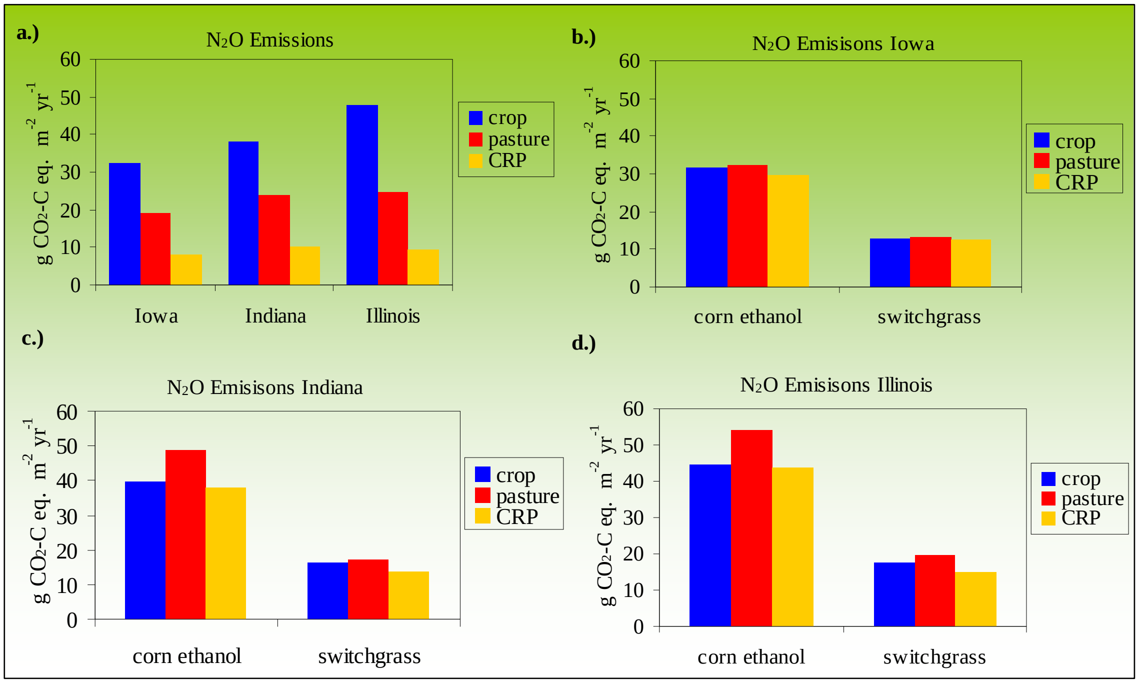


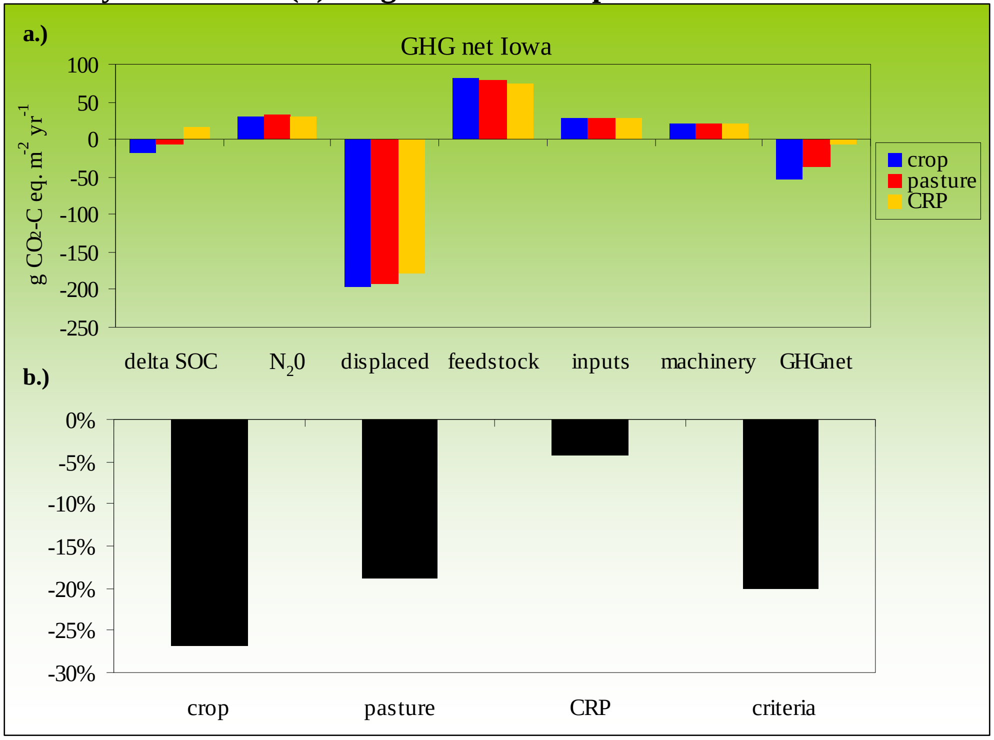
Figure 6. NO_3 leaching for crop (corn/soybean), pasture, and CRP lands in three states (a) and leaching for land converted from crop, pasture, and CRP to corn ethanol and switchgrass in Iowa (b), Indiana (c), and Illinois (d). Results are 10-year means.



Life Cycle Analyses for Total GHG Emissions

Feedstock conversion was the major GHG source and displaced fossil fuel was the main sink (Figure 7a). However, previous land use had an impact on soil CO_2 fluxes such that CRP lands converted lost SOC, while land that was in pasture or already cropped gained SOC. Of the three land use change options considered, cropland conversion exceeded the 20% reduction criteria, pasture conversion came close, and CRP conversion showed little net GHG reduction (Figure 7b).

Figure 7. Components of net greenhouse gas fluxes (GHG) from life cycle analysis of crop (corn/soybean), pasture, and CRP land converted to corn ethanol cropping in Iowa (a) and the reduction in GHG compared to burning fossil fuel for an equivalent amount of energy and the minimum GHG reduction for grain based ethanol from the Energy Independence and Security Act of 2007 (b). Negative values represent GHG sinks.



Limitations

This analysis has several limitations. The DAYCENT model results were from point simulations so variability in weather, soils, and land management within the states of Iowa, Indiana, and Illinois were not represented. We did not include leakage. That is, conversion of previously cropped land to biofuel production in the US is likely to be at least partially compensated by increasing cropped land areas in other parts of the world. A more complete accounting would include the GHG impacts of land use change in other countries resulting from biofuel cropping in the US. We assumed reduce tillage but did not include other improved land management practices such as nitrification inhibitors, which are expected to reduce both N gas emissions and NO_3 leaching. Lastly, the feasibility of ethanol production from cellulosic crops such as switchgrass has yet to be demonstrated on large scales.

4. Conclusions

Conversion of CRP lands to corn ethanol production would result in little net GHG savings compared to burning fossil fuel, greatly increase NO_3 leaching, and constrain other benefits of CRP land such as wildlife habitat. Conversion of pasture and crop land to corn ethanol cropping show GHG benefits, reductions in leaching for previously cropped systems, and increases in leaching for lands previously in pasture. Converting CRP land to switchgrass cropping would lessen the rate at which these soils store SOC, increase N_2O emissions, and have little impact on NO_3 leaching. Converting pasture and crop land to switchgrass cropping would increase SOC storage, decrease N_2O emissions, and decrease NO_3 leaching. These results highlight the importance of considering how current and previous land use interact to control soil storage and fluxes of C and N compounds.

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