The Lifecycle Carbon Footprint of Biofuels

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Soil Nitrous Oxide Emissions with Crop Production for Biofuel: Implications for Greenhouse Gas Mitigation

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Introduction

Biofuel production is growing in the United States with policies primarily aimed at developing alternative sources of fuel. An important secondary objective is to reduce greenhouse gas emissions associated with fossil fuel combustion. Biofuels can potentially reduce greenhouse gases because crops are a renewable resource of energy that absorb carbon emitted through the combustion process in subsequent growing seasons (Smith *et al*., 2007). However, greenhouse gas emissions are generated with crop production (Adler *et al*., 2007), such as fuel use during cultivation, planting, harvest, and transportation; as well as production of inputs such as fertilizer and herbicides (West and Marland, 2002). There are also changes in greenhouse gas fluxes associated with soil processes in cropland. Soil organic carbon (C) is converted into carbon dioxide (CO_2) with land use change to cropping (Davidson and Ackerman, 1993); although carbon can also be sequestered by adopting conservation management practices in fields that have been managed with conventional approaches (Paustian *et al*., 1997; Lal *et al*., 1998; Council for Agricultural Science and Technology, 2004). Soil nitrous oxide (N_2O) emissions are likely to be the largest source of greenhouse gas emissions associated with bioenergy crop production (Adler *et al*., 2007), but soil N_2O is also probably the least well quantified at larger regional scales (Crutzen *et al*., 2008). In fact, Crutzen *et al*. (2008) have suggested that soil N_2O emissions from bioenergy crop production are so large that there will be no greenhouse gas mitigation associated with replacing fossil fuels with biofuels.

N_2O is a trace gas emitted from soils through microbial processes of nitrification and denitrification (Firestone and Davidson, 1989). While the processes occur in soils without management, emissions are enhanced with practices that increase nitrogen (N) input to soils (Mosier *et al*., 1998). Key practices include mineral N fertilization, organic amendments and seeding symbiotic N-fixing plants, such as legumes, which are all common agricultural practices. In the United States, N_2O emissions associated with agricultural soil management are a national key source of greenhouse gas emissions (Environmental Protection Agency, 2007), and globally, N_2O is one of the greenhouse gases of critical concern due to large increase in atmospheric concentrations during the last century (Forster *et al*., 2007).

N_2O is emitted both directly in soils from mineral N additions and microbial transformations of organic N, and also indirectly with N losses through volatilization, leaching and runoff of N compounds that are converted into N_2O off-site (Eggleston *et al*., 2006). Much of the controversy surrounding the mitigation potential with biofuels is due to uncertainty in the indirect emissions. Using a top-down analysis based on change in atmospheric concentrations of N_2O, Crutzen *et al*. (2008) estimated that 3% to 5% of the mineral N added to cropland soils is eventually emitted as N_2O, and only about 1% of the total emissions is thought to be emitted directly in the soil according to Eggleston *et al*. (2006). Furthermore, Crutzen *et al*. (2008) suggest that the indirect emissions are not well quantified in biofuel lifecycle analyses using the method provided by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston *et al*., 2006). Indirect emissions of N_2O are not easy to measure in practice, leading to considerable uncertainty in their estimation, which further complicates these analyses. Regardless of the uncertainty, some N_2O is emitted indirectly from N that is lost from a cropland soil through volatilization, leaching and runoff, and therefore must be quantified to fully address greenhouse gas emissions associated with the lifecycle of biofuel production.

In addition to the availability of mineral N, N_2O emissions will also vary with environmental conditions, such as temperature, precipitation, pH and edaphic characteristics. Consequently, emissions will vary spatially and temporally; for example, Burton *et al*. (2008) found that emissions tend to be lower in semi-arid regions than the global average emissions estimated using the IPCC method (Eggleston *et al*., 2006). Regional variation in N_2O emissions could have important consequences for the net greenhouse gas mitigation associated with biofuel production.

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Our objectives were to estimate regional variation in soil N_2O emissions for two bioenergy crops, corn and soybeans, and then evaluate the net effect of N_2O emissions on reducing the benefit of biofuels for greenhouse gas mitigation, focusing on corn grain-based ethanol production in the Midwest.

Methods

We estimated soil N_2O emissions for corn and soybeans using the DAYCENT process-based model (Parton *et al*., 1998). DAYCENT simulates moisture and thermal regimes in soils, along with crop production, microbial decomposition, N mineralization, leaching, runoff, and N gas production. The model has been well tested with experimental data and applied to estimate N_2O emissions from US croplands for greenhouse gas emissions reporting (Del Grosso *et al*., 2001, 2006; Environmental Protection Agency, 2007). DAYCENT simulates many of the key processes influencing soil N_2O emissions, and therefore is better able to capture regional heterogeneity in emissions than simpler estimation approaches, such as the Intergovernmental Panel on Climate Change (IPCC) method (Eggleston *et al*., 2006). In general, DAYCENT estimates emissions with little or no bias, except at extremely high and low emission rates. An empirically-based approach has been developed to adjust for this error so that results are unbiased (Ogle *et al*., 2006; Del Grosso *et al*., forthcoming).

In order to simulate emissions, the model requires several input data representing environmental conditions and management activity influencing the microbial processes leading to N_2O emissions. The key input data include: 1) daily weather data from DAYMET program (Thornton *et al*., 2000); 2) edaphic characteristics from STATSGO soil database (Soil Survey Staff, 2005); 3) N fertilizer rates largely based on US Department of Agriculture (USDA) cropping surveys (Economic Research Service, 1997); 4) manure production and application from USDA and US Environmental Protection Agency (EPA) databases (Edmonds *et al*., 2003, Environmental Protection Agency, 2007); and 5) crop production from USDA/National Agricultural Statistics Service (NASS) (National Agricultural Statistics Service, 2000). See Environmental Protection Agency (2007) for a full list of data sources used in the simulations.

We used the agricultural regions delineated for the Agricultural Sector Model as the basis of the simulations (McCarl *et al*., 1993). There are 63 regions in the conterminous United States that are based on state boundaries, with further subdivisions in larger and more diverse states (Figure 1). Corn and soybeans were simulated with DAYCENT for each region in which farmers produced these crops in the year, 2000 according the National Agricultural Statistics (National Agricultural Statistics Service, 2000). Three time periods were simulated, including 1) pre-settlement period to establish initial conditions before settlement in the 1600s through 1800s; 2) base period of cultivation up to 1970; and 3) modern period of agriculture from 1970 through 2005.

DAYCENT was used to estimate the direct N_2O emissions occurring on-site, in addition to the N losses through leaching, runoff and volatilization. We used IPCC emission factors to estimate the N_2O emitted off-site associated with the N losses. Specifically, we used an emission factor of 0.01 kilogram (kg) N_2O-N/hectare (ha) for N_2O emissions associated with volatilization of N from sites, and 0.0075 kg N_2O-N/ha for N_2O emission from leaching and runoff of N from sites (Eggleston *et al*., 2006). All estimates represent the average between 2000 and 2006, given common management practices in each region.

In the second part of the analysis, we used the model-based assessment framework described above for soil N_2O in a life-cycle assessment to evaluate the net greenhouse gas benefit of ethanol production from corn grain in the Midwest. The life-

Figure 1: Agricultural Regions Delineated for the Agricultural Sector Model, which Formed the Basis for the Soil N_2O Emission Analysis.

cycle analysis was based on the approach developed by Adler *et al*. (2007), and addresses greenhouse gas emissions associated with following sources: 1) soil emissions including N_2O, methane (CH_4) uptake due to methanotrophic activity, and soil C stock changes; 2) fossil fuel energy requirements for chemical production of fertilizers, herbicides and other inputs (West and Marland, 2002); 3) feedstock conversion into ethanol including transportation from field to refinery and subsequent distribution; and 4) fuel usage associated with agricultural machinery based on the Integrated Farm System Model (Rotz, 2004) and American Society of Agricultural Engineers (ASAE) Machinery Standards Data (American Society of Agricultural Engineers, 2000). The ethanol yields were assumed to be 467 liter (L)/milligram (mg) dry matter (Wang, 2001), and net reduction in greenhouse gas emissions was based on the amount of displaced fossil fuel according to vehicle fuel economy ratios of fossil fuel to biofuel (Sheehan *et al*., 1998, 2004). The energy savings for co-products were also estimated based on the displacement method (Farrell *et al*., 2006).

We assumed a scenario of conversion from Conservation Reserve Program (CRP) land into corn production to meet biofuel demand in the near-term. Corn was simulated assuming adoption of conservation tillage (*i.e.*, reduced tillage) but with other conventional agronomic practices such typical fertilization rates for the region from USDA/Economic Research Service (ERS) cropping surveys (Economic Research Service, 1997). However, we did not simulate manure amendments following conversion to corn production, which would lead to higher N_2O emissions. An increase in crop production for biofuels is not likely to lead to a concomitant increase in livestock production, and thus no additional manure would be available for application on the newly developed cropland. Emissions were estimated on a CO_2 equivalent basis, with CH_4 and N_2O equivalent to 23 and 310 times the global warming potential of CO_2, respectively (Forster *et al*., 2007).

Results

Regional Soil N_2O Emission Patterns

Soil N_2O emission varied regionally and the lowest emissions tended to occur in New England, mid-Atlantic and Southeastern states (Figure 2). Emissions from corn were positively

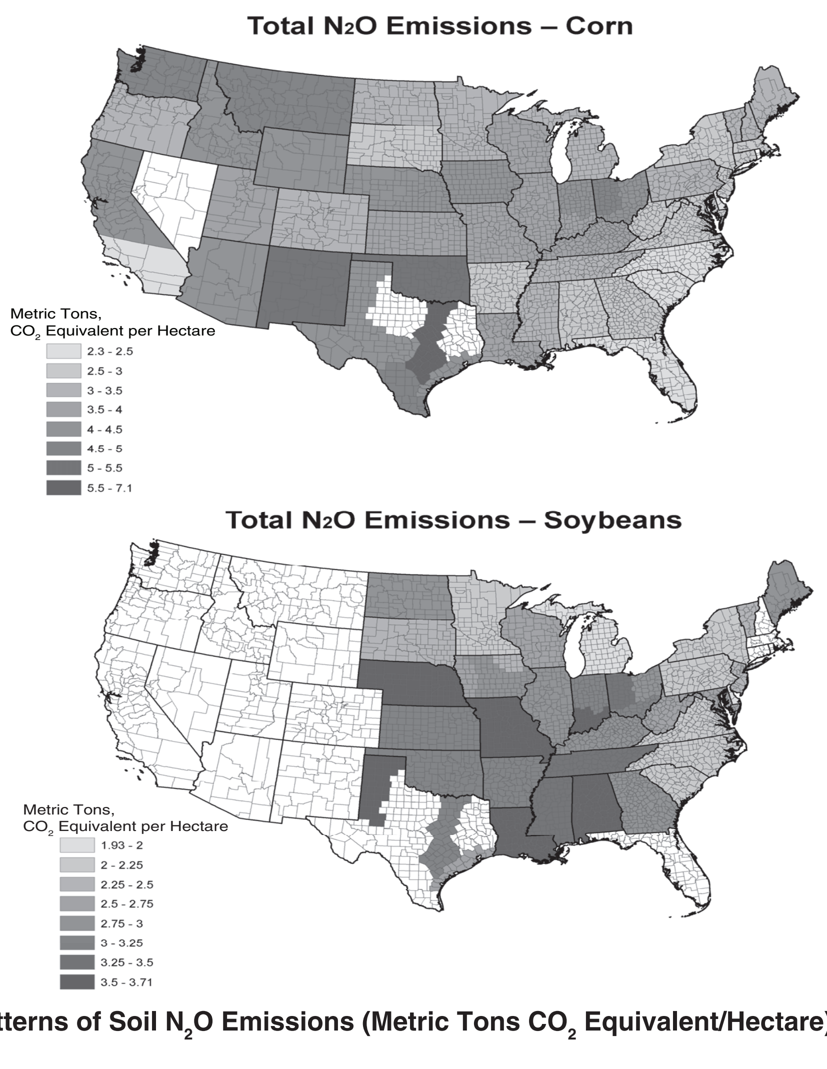

Figure 2: Regional Patterns of Soil N_2O Emissions (Metric Tons CO_2 Equivalent/Hectare) for Corn and Soybean Production.

correlated with the amount of N fertilization, in which higher rates of N addition led to more emissions. Soybeans are typically fertilized at lower rates because of their symbiotic N-fixing capability, and so fertilizer rates were not correlated with soil N_2O emissions for soybeans. Moreover, soybean production generated less soil N_2O emissions across the regions compared to corn production (Figure 2). However, the greenhouse gas mitigation also depends on the amount of fossil fuel displaced per unit area of crop production. Adler *et al*. (2007) found that the soybeans had less greenhouse gas emissions than corn in Pennsylvania, but corn production also has a considerably higher yield and displacement of fossil fuel on a per unit area basis. Further analysis is needed to determine if soybean production for biodiesel would lead to more greenhouse gas mitigation compared to corn production for ethanol.

On average, indirect emissions accounted for 14% of the total soil N_2O emissions from corn production across the 63 regions, and accounted for approximately 17% of the total soil N_2O emissions from soybean production (Figure 3 and 4). While indirect emissions are significant, direct emissions are the largest source of soil N_2O according to this analysis. In total, our results suggest that 2% to 2.5% of N added to soils is emitted as N_2O either directly onsite or indirectly with N loss through leaching, runoff and volatilization.

Greenhouse Gas Lifecycle Analysis for Ethanol Production in the Midwest

We analyzed a scenario whereby CRP lands would be converted into bioenergy crop production in the Midwest, un-

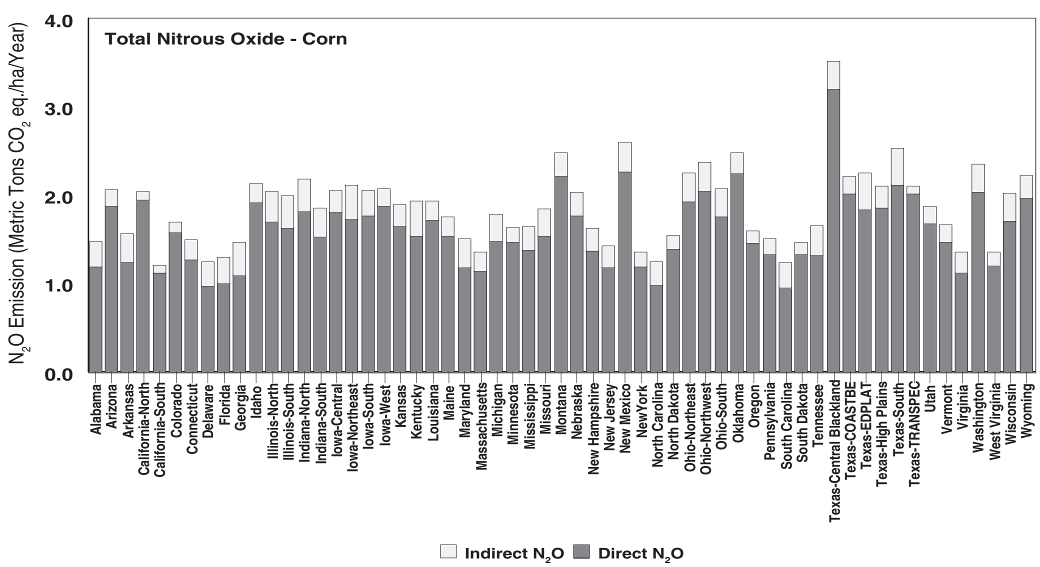

Figure 3: Direct and Indirect Soil N_2O Emissions Associated with Corn Production in the Agricultural Regions.

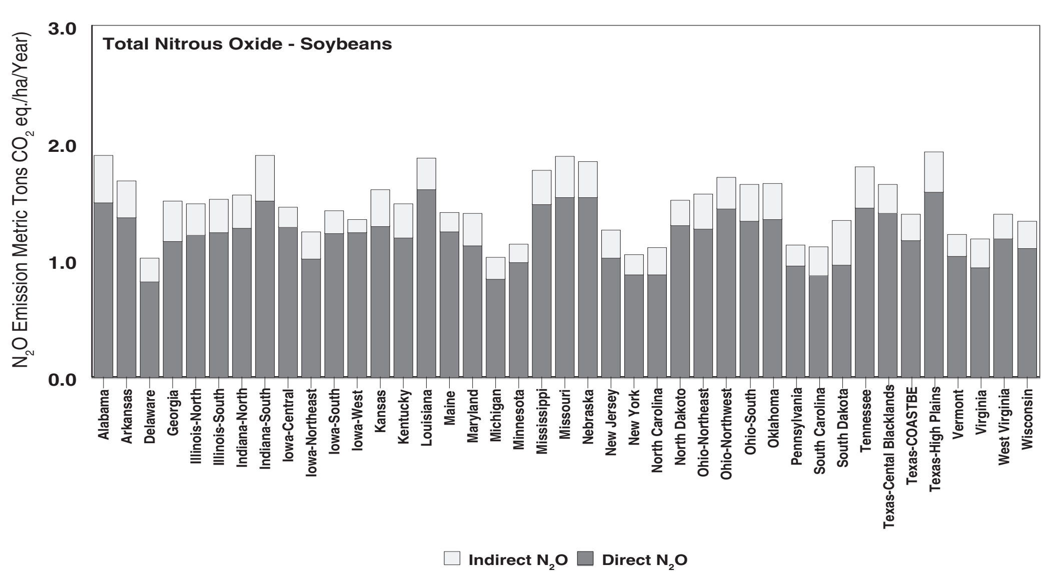

Figure 4: Direct and Indirect Soil N_2O Emissions Associated with Soybean Production in the Agricultural Regions.

der the assumption that existing crop production would be maintained to meet demand for food commodities and livestock feed (*i.e.*, assuming traditional food and feed demand would not decline). The largest source of emissions was associated with feedstock conversion in biofuel, approaching levels of 2.5 to 3 metric tons (mt) CO_2 equivalent (eq.) for a hectare of harvested corn grain. Feedstock conversion includes emissions associated with transportation of products and the refinery process (Figure 5).

For soil greenhouse gas (GHG) emissions, we simulated changes over a 10 year period and averaged the emissions for the lifecycle analysis. In addition, we assumed that the impact of biofuel production on soil N_2O would be the difference between N_2O emissions on CRP land compared to emissions under corn production. In general, emissions from the idle CRP land were approximately 20% of the soil N_2O emitted after conversion to corn production (Figures 4 and 6). Overall soil N_2O emissions accounted for 10% to 25% of the greenhouse gas emissions associated with ethanol production, and was the second largest source of emissions in most states (Figure 5). Soil C loss following conversion from CRP, fuel usage, and production of chemical inputs for the cropping systems were generally smaller emission sources, but had a similar magnitude as the soil N_2O.

In the short-term, corn grain-based ethanol production following conversion from CRP can reduce greenhouse gas emissions compared to fossil fuel combustion, although the mitigation is modest ranging from nearly no change to about

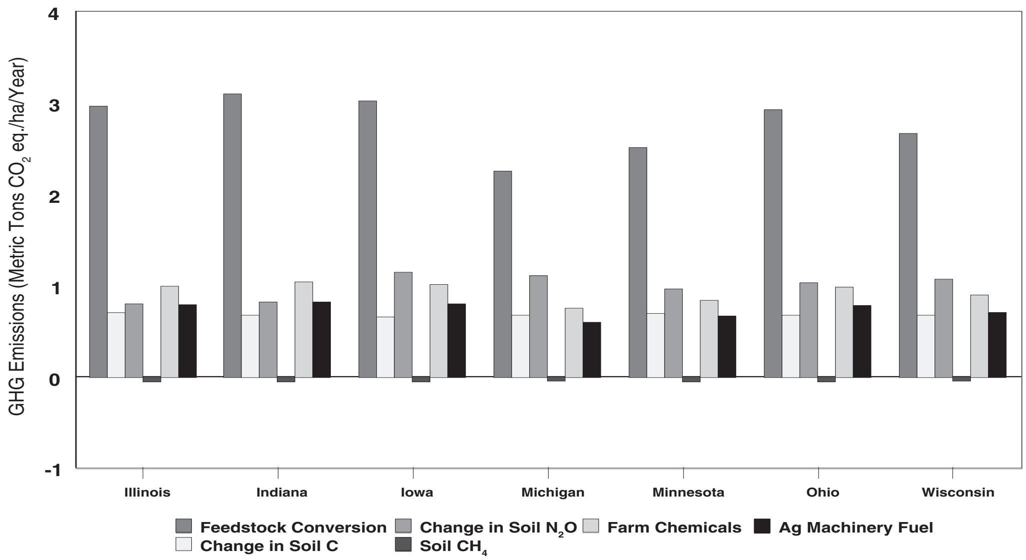

Figure 5: Greenhouse Gas Emissions (CO_2 Equivalents Metric Tons/Hectare/Year) Associated with Ethanol Production from Corn Grain in the Midwest During the First 10 Years Following Conversion from Land Enrolled in CRP.

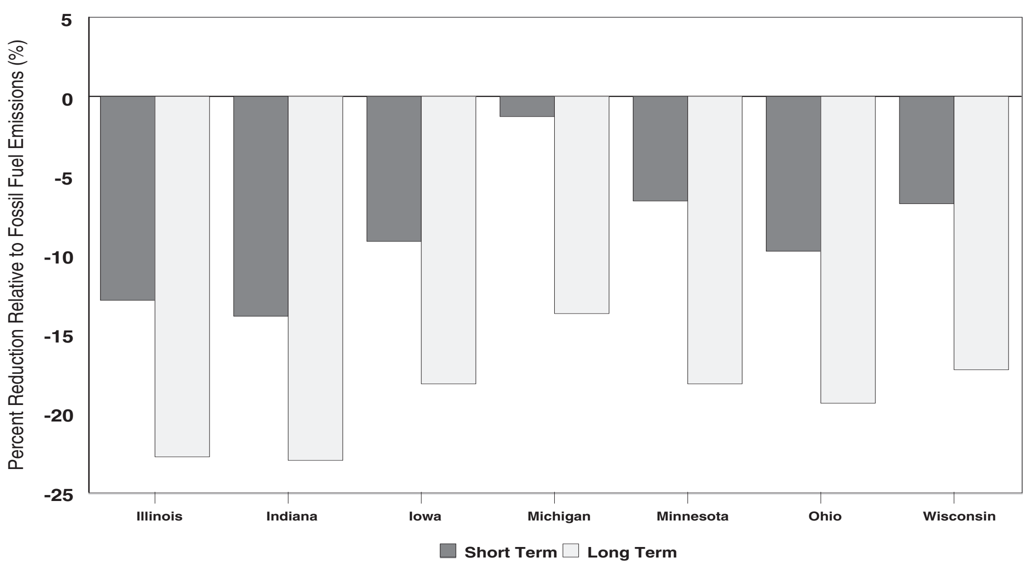

Figure 6: Greenhouse Gas Mitigation Associated with Substitution of Biofuel for Fossil Fuel on Per Unit Area Production of the Corn Production (CO_2 Equivalents Metric Tons/Hectare/Year).

15% (Figure 6). Mitigation potential increases from 15% to 25% in the long term assuming that soil C reaches a new near-equilibrium and that the other emission rates do not change.

Discussion

Soil N_2O emissions from crop production vary regionally with lowest rates of emissions tending to occur in New England, mid-Atlantic and Southeastern states. Further analysis will be needed to evaluate if the lower N_2O emissions would lead to more greenhouse gas mitigation through biofuel production in these regions. There would be an energy cost associated with converting land into crop production, and this could be relatively high if the conversion is from forestland to cropland. Integrated assessments would also be needed to consider the economics of corn and soybean production relative to current land uses, as well as the local interest in large scale corn and soybean production. Other factors contributing to net emissions that are expected to vary regionally include the distance from fields to the refinery, and the ability to exploit co-products from the biomass to energy conversion process.

We estimated an implied soil N_2O emission of 2% to 2.5% of N added to soils, which is lower than the 3% to 5% emission that was approximated by Crutzen *et al*. (2008). They suggest that indirect emissions are probably higher than previously thought by the IPCC (Eggleston *et al*., 2006), which may explain the discrepancy between the implied emission rates (*i.e.*, we used the IPCC factors to approximate the indirect emissions). If Crutzen *et al*. (2008) are correct, ethanol production from corn grain may lead to an increase in greenhouse gas emissions as they have suggested. However, there is uncertainty associated with the attribution of the N_2O emissions to biofuel production in their analysis. For example, Crutzen *et al*. (2008) evaluated the sensitivity of their results to the proportion of N_2O emissions from manure management. It is probably realistic to assume N_2O emissions from manure management are unrelated to biofuel production, and they found that removing this emission source did increase the likelihood of greenhouse gas mitigation with biofuel production. Crutzen *et al*. (2008) also suggested that the mitigation potential could be higher depending on the N use efficiency of crops and on the production of co-products from waste generated during the feedstock conversion process. Further research is needed into the attribution of total global N_2O emissions to crop production for biofuel commodities, and also to reduce the uncertainty in the indirect emissions.

Regardless of the discrepancy between estimates, the direct soil N_2O emissions could be reduced through adoption of improved N management practices, such as 1) avoiding over-application of fertilizer by using soil testing information and applying N at a rate to meet crop demand; 2) using precision-farming practices to apply N at the time of crop demand (*e.g.*, avoiding fall and other out of season applications); and 3) using nitrification inhibitors (Smith *et al*., 2007). For example, nitrification inhibitors may reduce N_2O emissions by 10% to 15% according to analyses using DAYCENT (Del Grosso, forthcoming). Options 1 and 2 would also decrease the indirect emissions of soil N_2O.

While ethanol production from corn production does appear to have a modest potential for decreasing greenhouse gas emissions relative to fossil fuel combustion, other bioenergy crops will likely provide more significant reductions in greenhouse gas emissions. For example, in the case study by Adler *et al*. (2007), ethanol and biodiesel from corn-soybean rotations reduced greenhouse gas emissions by about 40%, which included a 50% stover harvest for cellulosic-based ethanol production. This reduction was about two times greater than using ethanol produced from corn grain alone. However, using switchgrass (*Panicum virgatum*) and hybrid poplar (*Populus sp.*) would produce nearly a three-fold greater reduction in greenhouse gas emissions compared to corn-soybean rotations. These reductions were for long-term scenarios that assume soil carbon sequestration was limited, but soil carbon sequestration could be significant in the near-term. Moreover, they found that gasification of switchgrass and hybrid poplar yielded more than four times the greenhouse gas emission reductions of ethanol production from corn. Schmer *et al*. (2008) have also estimated greater greenhouse gas emission reduction with ethanol production from switchgrass using a lifecycle analysis, approximating a potential 94% reduction in emissions with fossil fuel displacement using a cellulosic-based process to produce ethanol.

Converting land into bioenergy crop production may have other un-intended impacts such as a reduction in supply of food, fiber and forage; loss of biodiversity; and contribute to an increase in tropical deforestation (Scharlemann and Laurance, 2008). Biofuel crop production may also contribute to other types of pollution such as nitrate leaching in groundwater and rivers. The sustainability of land parcels for crop production should also be evaluated when bringing land into bioenergy crop production. Climate change policy to reduce greenhouse gas emissions is likely to be most effective for farmers as well as society in general when developed with consideration of sustainability and avoiding other environmental problems to the extent possible.

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References

Adler, Paul R., Stephen J. Del Grosso and William J. Parton. "Life-Cycle Assessment of Net Greenhouse-Gas Flux for Bioenergy Cropping Systems." *Ecological Applications* 17(3)(April 2007):675-691. [Accessed April 2, 2008.] Available from http://www.esajournals.org/archive/1051-0761/17/3/pdf/i1051-0761-17-3-675.pdf

American Society of Agricultural Engineers. "Agricultural Machinery Management." ASAE D497.4 and EP496.2. In *ASAE Standards*. 47th edition. Saint Joseph, MI: American Society of Agricultural Engineers, 2000.

Burton, Louise, Ralf Kiese, David Gatter, Klaus Buttterbach-Bahl, Renee Buck, Christoph Hinz and Daniel V. Murphy. "Nitrous Oxide Emissions from Cropped Soil in a Semi-Arid Climate." *Global Change Biology* 14(1)(January 2008): 177-192.

Council for Agriculture Science and Technology. *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture*. Ames, IA: Council for Agriculture Science and Technology, 2004.

Crutzen, P.J., A.R. Mosier, K.A. Smith and W. Winiwarter. "N_2O Release from Agro-Biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels." *Atmospheric Chemistry and Physics* 8(2)(2008):389-395. [Accessed April 2, 2008.] Available from http://www.atmos-chem-phys.net/8/389/2008/acp-8-389-2008.pdf

Davidson, Eric A. and Ilse L. Ackerman. "Changes in Soil Carbon Inventories Following Cultivation of Previously Untilled Soils." *Biogeochemistry* 20(3)(September 1993):161-193. [Accessed April 2, 2008.] Available from http://www.springerlink.com/content/6617u13k3561vw04/fulltext.pdf

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel. "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In: M.J. Schaffer, Liwang Ma and Soren Hansen (eds.) *Modeling Carbon and Nitrogen Dynamics for Soil Management*. Boca Raton, FL: CRC Press, 2001.

Del Grosso, Stephen J., William J. Parton, Arvin R. Mosier, Marie K. Walsh, Dennis S. Ojima, P.E. Thornton. "DAYCENT National Scale Simulations of N_2O Emissions from Cropped Soils in the USA." *Journal of Environmental Quality* 35(4)(July 2006):1451-1460. [Accessed April 2, 2008.] Available from http://jeq.scijournals.org/cgi/reprint/35/4/1451

Del Grosso, S.J., S.M. Ogle, and F.J. Breidt. In prep. "Uncertainty in Estimating Nitrous Oxide Emissions from Cropped and Grazed Soils in the USA." Manuscript in preparation.

Edmonds, Larry, Noel Gollehon, Robert L. Kellogg, Barry Kintzer, Lynn Knight, Charles Lander, Jerry Lemunyon, Dan Meyer, David C. Moffitt and Jerry Schaeffer. *Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans*. Part 1 – Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Washington, DC: US Department of Agriculture, Natural Resource Conservation Service, June 2003. [Accessed April 2, 2008.] Available from http://www.nrcs.usda.gov/technical/NRI/pubs/cnmp1full.pdf

Economic Research Service. *Cropping Practices; 1990-95 Data*. Stock Number 93018. Washington, DC: US Department of Agriculture, Economic Research Service, 1997. [Accessed April 2, 2008.] Available from http://www.ers.usda.gov/data/archive/93018/

Eggleston, Simon, Leandro Buendia, Kyoko Miwa, Todd Ngara and Kiyoto Tanabe (eds). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. A report prepared by the Task Force on National Greenhouse Gas Inventories of the Intergovernmental Panel on Climate Change. Hayama, Japan: Institute for Global Environmental Strategies, 2006. [Accessed April 2, 2008.] Available from http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm

Environmental Protection Agency. *Climate Change – Greenhouse Gas Emissions. U.S. Greenhouse Gas Inventory Reports*. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. Washington, DC: US Environmental Protection Agency, 2007. [Accessed April 2, 2008.] Available from http://epa.gov/climatechange/emissions/usinventoryreport.html

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O'Hare and Daniel M. Kammen. "Ethanol Can Contribute to Energy and Environmental Goals." *Science* 311(5760)(January 27, 2006):506-508. [Accessed April 2, 2008.] Available from http://www.sciencemag.org/cgi/reprint/311/5760/506.pdf

Firestone, M.K. and E.A. Davidson. "Microbiological Basis of NO and N_2O Production and Consumption in Soil." In: Andreae, M.O. and D.S. Schimel (eds.) *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*. Chichester, England: John Wiley and Sons Ltd., 1989.

Forster, Piers, Venkatachalam Ramaswamy, Paulo Artaxo, Terje Berntsen, Richard Betts, David W. Fahey, James Haywood, Judith Lean, David C. Lowe, Gunnar Myhre, John Nganga, Ronald Prinn, Graciela Raga, Michael Schulz and Robert Van Dorland. "Changes in Atmospheric Constituents and in Radiative Forcing." In: Susan Solomon, Dahe Qin, Martin Manning, Melinda Marquis, Kristen B. Averyt, Melinda M.B. Tignor, Henry L. Miller and Zhenlin Chen (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press, February 2007. [Accessed April 2, 2008.] Available from http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Chelsea, MI: Sleeping Bear Press, 1998.

McCarl, B.A., C.C. Chang, J.D. Atwood and W.I. Nayda. *Documentation of ASM: The U.S. Agricultural Sector Model*. Technical Report TR-93. College Station, TX: Texas Agricultural Experimental Station, 1993.

Mosier, A. R., J.M. Duxbury, J.R. Freney, O. Heinemeyer and K. Minami. "Assessing and Mitigating N_2O Emissions from Agricultural Soils." *Climatic Change* 40(1)(September 1998):7-38.

National Agricultural Statistics Service. *Agricultural Statistics 2000*. Washington, DC: U.S. Government Printing Office, 2000. [Accessed April 2, 2008.] Available from http://www.usda.gov/nass/pubs/agr00/acro00.htm

Ogle, Stephen M., F. Jay Breidt and Keith Paustian. "Bias and Variance in Model Results Due to Spatial Scaling of Measurements for Parameterization in Regional Assessments." *Global Change Biology* 12(3)(March 2006): 516-523. [Accessed April 2, 2008.] Available from http://www.blackwell-synergy.com/doi/pdf/10.1111/j.1365-2486.2006.01106.x

Parton, W. J., M. Hartman, D. Ojima and D. Schimel. *DAYCENT and its Land Surface Submodel: Description and Testing. Global and Planetary Change* 19(1)(December 1998): 35-48.

Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noordwijk and P.L. Woomer. "Agricultural Soils as a Sink to Mitigate CO_2 Emissions." *Soil Use and Management* 13(s4)(December 1997): 230-244. [Accessed April 2, 2008.] Available from http://www.blackwell-synergy.com/doi/pdf/10.1111/j.1475-2743.1997.tb00594.x

Rotz, Clarence A. *The Integrated Farm System Model: a Tool for Developing More Economically and Environmentally Sustainable Farming Systems for the Northeast*. NABEC-04-0022. Saint Joseph, MI: American Society of Agricultural Engineers, 2004.

Schmer, M.R., K.P. Vogel, R.B. Mitchell and R.K. Perrin. "Net Energy of Cellulosic Ethanol from Switchgrass." *Proceedings of the National Academy of Sciences of the United States* 105(2)(January 15, 2008): 464-469. [Accessed April 2, 2008.] Available from http://www.pnas.org/cgi/reprint/0704767105v1

Sheehan, John, Vince Camobreco, James Duffield, Michael Graboski and Housein Shapouri. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*. NREL/SR-580-24089. Golden, CO: US Department of Energy, National Renewable Energy Laboratory, May 1998. [Accessed April 2, 2008.] Available from http://www.nrel.gov/docs/legosti/fy98/24089.pdf

Sheehan, John, Andy Aden, Keith Paustian, Kendrick Killian, John Brenner, Marie Walsh and Richard Nelson. "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol." *Journal of Industrial Ecology* 7(3-4)(2004):117-146. [Accessed April 2, 2008.] Available from http://devafdc.nrel.gov/pdfs/8427.pdf

Smith, Pete, Daniel Martino, Zucong Cai, Daniel Gwary, Henry Janzen, Pushpam Kumar, Bruce McCarl, Stephen Ogle, Frank O'Mara, Charles Rice, Bob Scholes, Oleg Sirotenko. "Agriculture." In: Bert Metz, Ogunlade R. Davidson, Peter R. Bosch, Rutu Dave and Leo A. Meyer (eds). *Climate Change, 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007. [Accessed April 2, 2008.] Available from http://www.mnp.nl/ipcc/pages_media/FAR-4docs/final_pdfs_ar4/Chapter08.pdf

Soil Survey Staff. *State Soil Geographic (STATSGO) Database*. Washington, DC: US Department of Agriculture, National Resources Conservation Service, 2005. [Accessed April 2, 2008.] Available from http://www.soils.usda.gov/survey/geography/statsgo/

Thornton, P.E., H. Hasenauer and M.A. White. "Simultaneous Estimation of Daily Solar Radiation and Humidity from Observed Temperature and Precipitation: An Application Over Complex Terrain in Austria." *Agricultural and Forest Meteorology* 104(4)(September 2000): 255-271.

Wang, M.Q. *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*. ANL/ESD/TM-163. Argonne, IL: Argonne National Laboratory, June 2001. [Accessed April 2, 2008.] Available from http://www.transportation.anl.gov/pdfs/TA/153.pdf

West, T.O. and G. Marland. "A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States." *Agriculture, Ecosystems & Environment* 91(1)(September 2002):217-232.