

# CH<sub>4</sub> AND N<sub>2</sub>O EMISSION MITIGATION POTENTIAL IN AGROECOSYSTEMS: ROLE OF GIS AND PROCESS-BASED MODELS IN ASSESSING PROJECT-LEVEL MITIGATION OPTIONS.

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**Subject Areas:** Agricultural sources of CH<sub>4</sub> and N<sub>2</sub>O; project-level mitigation options; agricultural soil management.

## Abstract

Agroecosystems represent an important opportunity for greenhouse gas mitigation projects through carbon sequestration in soils and reductions in CH<sub>4</sub> and N<sub>2</sub>O emissions. Biogeochemical processes that control CH<sub>4</sub> and N<sub>2</sub>O emissions from agroecosystems, like denitrification, nitrification, decomposition and fermentation, are non-linearly coupled with anthropogenic and ecological drivers that are highly variable in space and time. Static emission factors (EFs) do not capture this variability without detailed site and management specific EFs. In addition, EFs typically do not provide estimates of uncertainties particular to a set of conditions, a key requirement for assessing the efficacy of mitigation options. Therefore, project level assessments of potential impact of agricultural management on CH<sub>4</sub> and N<sub>2</sub>O need to be done in a modeling context. GIS process-based models are now mature and scientifically sound enough to simulate spatially heterogeneous conditions that control temporal and spatial patterns of greenhouse gases (GHG) and are critical for project level studies. In particular, models can be used to compare and evaluate alternative management practices, assess co-impacts of management decisions (e.g. coupling between carbon sequestration and CH<sub>4</sub> & N<sub>2</sub>O emission), simulate long-term permanence of mitigation, develop baselines for quantifying net effects of management decisions, and provide comprehensive impact assessment beyond GHG emission mitigation through simulation of nutrient flows. It is also noteworthy that models are especially required for the monitoring and verification phases CH<sub>4</sub> and N<sub>2</sub>O mitigation projects in agroecosystems given the prohibitive costs for direct measurements. This paper presents an overview of a decision support system for estimating carbon sequestration, CH<sub>4</sub> and N<sub>2</sub>O mitigation potential at the project level. The system utilizes GIS databases, a process-based biogeochemical model called Denitrification-Decomposition, or DNDC, and statistical sampling techniques. The system provides temporally and spatially explicit estimates of carbon sequestration, CH<sub>4</sub> and N<sub>2</sub>O emissions. System will provide uncertainties based on uncertainties in input data (e.g. management, soils) and model assumptions (e.g. crop growth and carbon allocation).

## **1.0 Introduction**

Agriculture represents a significant opportunity for greenhouse gas mitigation projects through soil carbon sequestration and reductions of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions. Recently, significant investments are being made in assessing carbon sequestration projects in agricultural soils due to the potential for trading carbon credits coupled with significant environmental benefits through improved soil quality, soil fertility and reduced erosion potential. Changes in farming management practices, such as tillage, fertilization, irrigation, manure amendment etc., are currently being evaluated for their potential in mitigating greenhouse gases emitted from the agricultural sector. For example, it has been widely reported that replacing conventional tillage with no-till results in soil organic carbon (SOC) storage (Lal et al. 1999). The carbon (C) sequestration potential of agricultural lands is being studied with experimental or modeling approaches in a number of on going research projects (e.g. Eve et al. 2002, Falloon et al. 2002, Paustin et al. 2002, Rickman et al. 2002.). Long-term clearing, tilling, and draining of natural soils for agricultural production has released large amounts of carbon dioxide to the atmosphere from the soils' fertile soil organic matter (Lal et al. 1999). The soil organic matter in topsoil has depleted 40 to 60% of the original soil organic carbon (Cambardella, 1992). Lal (1998) estimated the loss of soil organic content from U.S. cropland soils at about 5 Pg. Therefore, U.S. cropland has a potential to sequester approximately 5 Pg of carbon through improved soil management practices (Lal, 2000). Robertson's studies (2000) at the Kellogg Biological Station (KBS) Long Term Ecological Research site (LTER) showed that fields that have never been in agricultural production contain 40% to 50% more carbon by weight than active agricultural fields. Agricultural fields under no-till conservation tillage cropping methods were found to sequester 300 kg carbon per hectare per year, whereas conventionally tilled crops exhibited no annual carbon sequestration (Robertson, 2000). Other estimates of carbon sequestration rates for conservation tillage range from 500 kg/C/ha/yr to 600 kg/C/ha/yr (Lal, 1998). The United States Department of Energy also estimates the conversion from conventional tillage to conservation tillage methods to potentially sequester 300 kg C/ha/yr. Unfortunately, most of the published research focused only on the soil C dynamics with little of attention to other greenhouse gases, namely nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) which may offset gains in greenhouse gas emissions if not managed properly. Few of the reports assessed the impacts of the C sequestration induced by the management alternatives on N<sub>2</sub>O or CH<sub>4</sub> emissions from the same lands. Actually, there is an inherent relation between C storage and N<sub>2</sub>O or CH<sub>4</sub> emissions in agricultural soils.

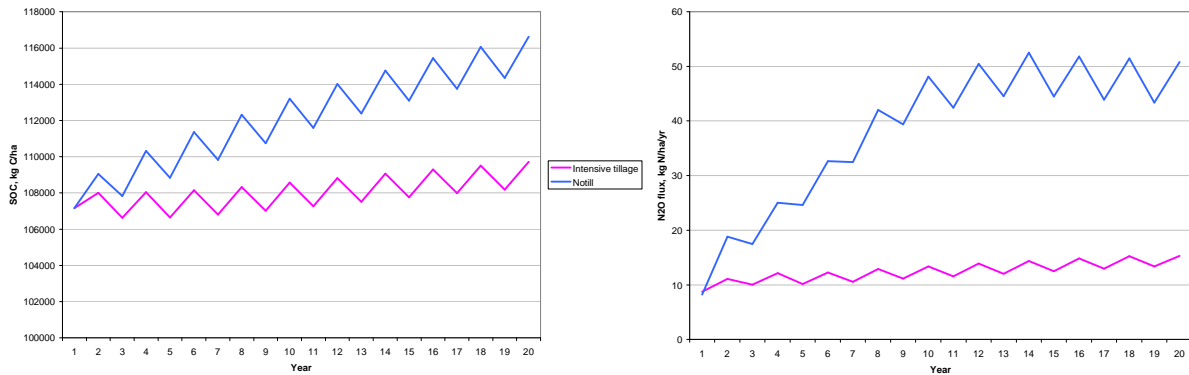
## **2.0 Need for Spatially and Temporally explicit Process Based models**

Biogeochemical processes that control CH<sub>4</sub> and N<sub>2</sub>O emissions from agroecosystems, like denitrification, nitrification, decomposition and fermentation, are non-linearly coupled with anthropogenic and ecological drivers that are highly variable in space and time. As a result, static emission factors (EFs) cannot capture this variability without development of detailed site and management specific EFs. While site and management specific emission factors may be able to

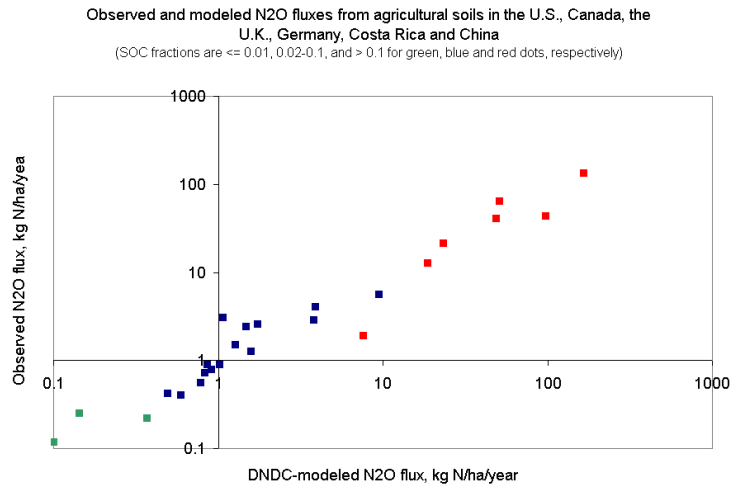
capture unique characteristics of a particular site at a given time, the characteristics change with time (e.g. soil carbon sequestration resulting from a shift from conventional tillage to no-till agricultural). To demonstrate this, we conducted a case study with our soil biogeochemical model called Denitrification-Decomposition or DNDC to predict the impacts of alternative tillage practices on both SOC and N<sub>2</sub>O for Adair County in Iowa, a typical corn-soybean producing area. Two scenarios, conventional tillage and no-till, were run for 20 years for the corn-soybean rotated farmland under the local typical climate, soil and management conditions. The modeled results (see table 1 and Figure 1) indicated shifting tillage from conventional to no-till increased C sequestration from 125 to 468 kg C/ha, and also increased average N<sub>2</sub>O emissions from 11.5 to 21.2 kg N/ha per year for the 20 years. Since the global warming potential (GWP) of N<sub>2</sub>O is 310 times higher than that of CO<sub>2</sub> in a 100-year basis, the magnitude of the GWP value induced by C sequestration (1258 kg CO<sub>2</sub> equivalent/ha/yr) was smaller than the GWP value induced by the increased N<sub>2</sub>O emissions (4687 kg CO<sub>2</sub> equivalent/ha/yr).

**Table 1.** DNDC-modeled C sequestration, N<sub>2</sub>O emissions and their global warming potentials (GWP) for a corn-soybean rotation system with different tillage approaches in Adair County, Iowa from 1994-2014

|                   | C sequestration | N <sub>2</sub> O flux | SOC-GWP                             | N <sub>2</sub> O-GWP | Net GWP |
|-------------------|-----------------|-----------------------|-------------------------------------|----------------------|---------|
|                   | kg C/ha/yr      | kg N/ha/yr            | kg CO <sub>2</sub> equivalent/ha/yr |                      |         |
| Intensive tillage | 125             | 11.5                  | -459                                | 5615                 | 5156    |
| Notill            | 468             | 21.1                  | -1716                               | 10301                | 8585    |



Since C sequestration and N<sub>2</sub>O emission are both affected by many environmental factors but in different ways, shifting from one location to another will inherently alter the effects of any management alternatives on the net GWP. DNDC with its fundamental biogeochemical processes can quantify the net GWP effects of alternative management practices across climatic zones, soil types, and management regimes and coupled with GIS data for regional assessments. Figure 2 highlights that (a) DNDC modeled fluxes of N<sub>2</sub>O match observed fluxes and (b) the tight coupling between SOC and N<sub>2</sub>O emissions.



**Figure 2.** Comparison of observed with DNDC-modeled N<sub>2</sub>O fluxes from agricultural sites in the U.S., Canada, the U.K., Germany, Costa Rica, and China. The red dots are the sites with SOC contents higher than 10%, the blue dots 1%-10%, and the green dots ≤ 1%. The DNDC-modeled N<sub>2</sub>O fluxes are not only in agreement with observations but also reflecting the SOC/N<sub>2</sub>O relationship. The field data from Mosier et al., 1981, Ryden 1983, Terry et al. 1981, Crill 2000, Zheng et al. 1999, Smith et al. 2002, Brown et al. 2002, and Flessa et al. 1996, Wang et al. 1997.

If carbon sequestration in agricultural soils is to become a viable commodity in the emerging carbon markets, then methods are needed to predict, monitor and validate not only changes in soil carbon stocks over time, but also the impacts on non-CO<sub>2</sub> GHG, like CH<sub>4</sub> and N<sub>2</sub>O. It is clear that direct measurement of changes in soil carbon content and trace gas fluxes is economically not reasonable. Therefore, approaches that rely on spatially explicit process based models coupled with direct measurements to validate and constrain uncertainties in model estimates are likely the most cost effective and efficient. Process-based models clearly have an important role in designing, evaluating and implementing carbon sequestration and CH<sub>4</sub> and N<sub>2</sub>O mitigation projects. In particular, models can

- provide opportunities for assessing potential soil carbon sequestration rates (project evaluation phase),
- be used for scenario analyses to examine risks (e.g. climate variability),
- simulate secondary impacts of agricultural carbon sequestration projects on net GWP during project phase and beyond (long-term),
- provide guidance on monitoring phase of carbon contracts by verifying changes in soil carbon stocks over time at the contract target levels,

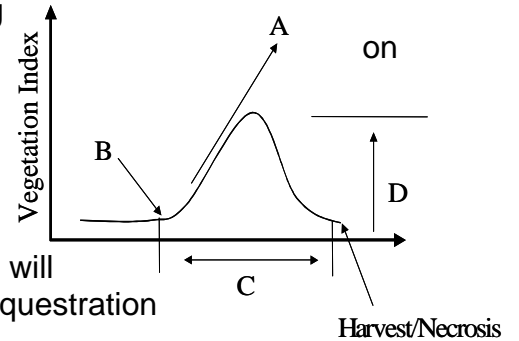
- be used to adjust predicted (or potential) values, that are based on predicted climate, soil, and management conditions, to simulated actual conditions (critical for monitoring), and
- be augmented with direct observations to assess reliability of model predictions, adjust model inputs, and provide updates to overall uncertainties.

### 3.0 Decision support system

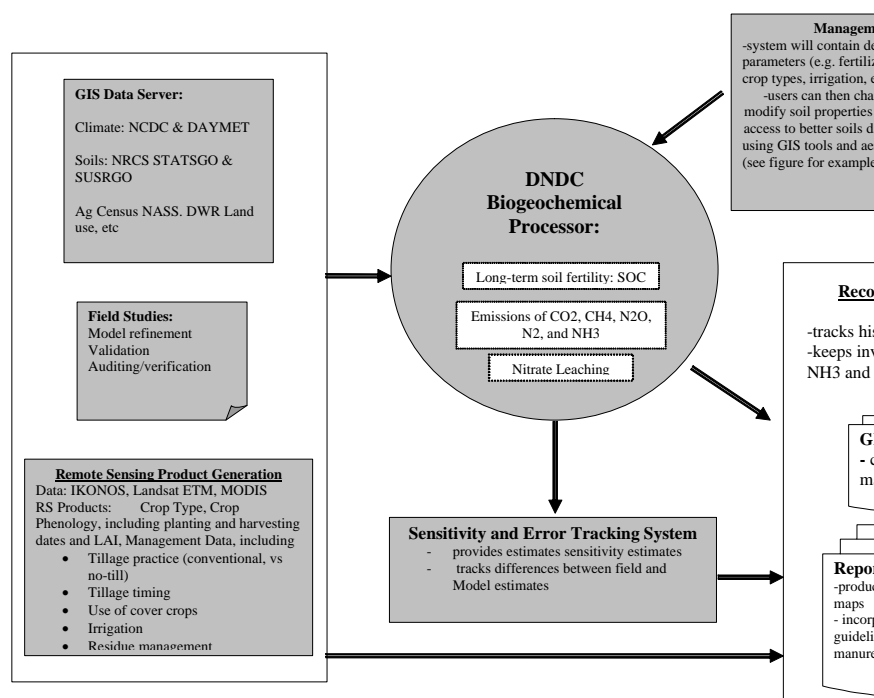
To estimate the impacts of alternative management policies on greenhouse gas mitigation at local, regional and project level scales, the DNDC model must be driven by the spatially differentiated information of climate, soil properties, crop type and rotation, and other cropping management practices such as tillage, fertilization, manure amendment, irrigation, grazing etc. Databases supported with remote sensing analysis are built to integrate all of the input parameters in a GIS framework. The linked biogeochemical model and GIS database will form the basis of a decision support system to serve comprehensive analysis for agricultural mitigation strategies. While we have developed critical components of our decision support system, we are enhancing our system for better assessment of project-level mitigation options. Figure 3 outlines the framework of our system.

- **Biogeochemical Processor.** DNDC is being utilized as a core model of the Decision Support System. Over the past decade, multi-agency support from NASA, USEPA, USDA and NSF has guided our development, testing, and application of a research biogeochemical model of N and C cycling in soils based on the biogeochemical concepts outlined above (Li et al. 1992, 1994, 1996; Li 2000). The DNDC model was constructed with two components to reflect the two-level driving forces that control geochemical and/or biochemical processes related to C and N fluxes. The first component, consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles (ammonium, nitrate, dissolved organic carbon) based on ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts NO, N<sub>2</sub>O, CH<sub>4</sub> and ammonia (NH<sub>3</sub>) fluxes based on the soil environmental variables. Classical laws of physics, chemistry and biology, and empirical equations generated from laboratory observations, were used in the model to parameterize each specific reaction. The entire model forms a bridge between basic ecological drivers including management of agro-ecological systems, and water, C and N cycles. DNDC utilizes databases with spatially and temporally differentiated information on climate, soil, vegetation and farming practices as parameters for supporting local, regional and national scale analyses. Details on DNDC are provided in paper by Li et al.
- **Agricultural Management Observatory:** (spatial and temporal monitoring of actual management practices and crop development is critical for refining model simulations). This component focuses on research on algorithm development and remote sensing applications for generating data necessary for a decision support system for modeling agricultural greenhouse gas.

Phenologic information for mapping cropping practices can be observed with multi-temporal EVI (Enhanced Vegetation Index) Multitemporal EVI development curves (see insert) are plotted against time and thresholds will be established for each cover type to indicate the onset (B), growth rate (A), maximum potential growth (D), time corresponding to the maximum (senescence), and harvest. Remote sensing products will include crop phenology (e.g. crop type, planting and harvesting dates, LAI development) and management data tillage practice and timing. (e.g. conventional, conservation or no till), conservation buffers, use of cover crops, residue management, irrigation practices. Remote sensing provides a unique opportunity for tuning model predictions as well as mapping actual management practices, which will be useful for monitoring of carbon sequestration projects/contracts.



- **GIS Database Management and Product Generation System:** This component will focus on developing databases on soils, climate and management practices. For example, for the US we are utilizing the NRCS STATSGO and SSURGO soils data. Statistical modeling of soil characteristics will be performed to examine impact of variability and uncertainty in soil characteristics on model simulations. For the US we are using daily climate station data and working on linking directly to DAYMET to get daily gridded data on temperature, precipitation, relative humidity, solar radiation. County scale agricultural census data also being compiled from NASS and Landsat based maps from the NASS Cropland Program.
- **Sensitivity and error tracking system:** Coupled with these inventories are uncertainty analyses that focus on quantifying how biophysical factors (e.g. soil properties), environmental conditions (e.g. precipitation, temperature) and



management alternatives (e.g. amount and timing of fertilizer/manure application, types of manure application, tillage, irrigation) impact the production of GHG and changes in terrestrial C stocks. Uncertainties generated from the modeled processes as well as from the input data sets are assessed through single parameter sensitivity analyses and multi-parameter analyses using Latin Hypercube Sampling (LHS McKay et al. 1979). LHS is similar in concept to Monte Carlo sensitivity analysis, but does not require as many sample runs. Since Monte Carlo analysis is based on purely random sampling, it requires a large number of samples to provide statistically valid results. LHS is based on a stratified sampling approach that can create statistically significant results with significantly fewer model runs. The LHS technique ensures that the entire range of each variable is sampled. A statistical summary of the model results will produce indices of sensitivity and uncertainty that relate the effects of heterogeneity of input variables to model predictions.

#### **4.0 Conclusion:**

Agriculture is a critical for the provision of food and fiber. Agriculture also represents a significant opportunity for greenhouse gas mitigation projects through soil carbon sequestration and reductions of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions. Projects that result in soil carbon sequestration and reductions in CH<sub>4</sub> and N<sub>2</sub>O emissions often result in compound environmental benefits through improved soil structure which in turn can improve air and water quality and sustainability of agroecosystems. However, it is also well known that carbon sequestration can inherently increase N<sub>2</sub>O (in upland soils) and CH<sub>4</sub> (in wetland soils) emissions due to the coupling of carbon and nitrogen biogeochemical cycles. Thus, the net offset between reductions in atmospheric CO<sub>2</sub> and increases in atmospheric CH<sub>4</sub> and N<sub>2</sub>O can be significant, and in some cases can result in a net increase in atmospheric CO<sub>2</sub> equivalents. Therefore, assessing the efficacy of carbon sequestration projects or CH<sub>4</sub> and N<sub>2</sub>O mitigation in forestry and agriculture would benefit from methods that capture spatially and temporally explicit nature of the processes that control C and N cycling.

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