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A regional scale modeling framework combining biogeochemical model with life cycle and economic analysis for integrated assessment of cropping systems

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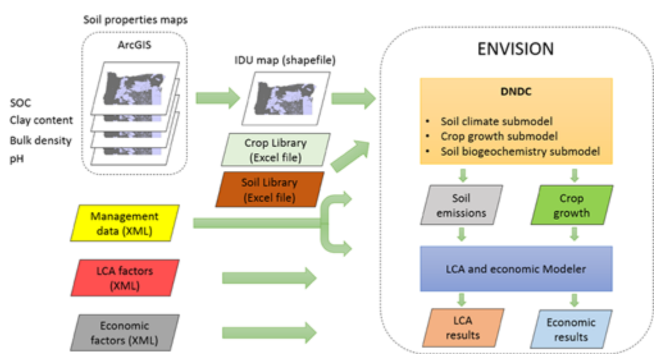
HIGHLIGHTS

- Integrates DNDC model with LCA and economic analysis in ENVISION.
- Integrated analysis of cropping systems over long periods at regional scale.
- The variation in soil emissions due to variation in weather is high.
- Study area GHG emissions ranged −1389 to 6000 kg CO-eq/ha/2-year cropping system.
- Most farms did not break-even under low/medium prices for corn and soybean.

GRAPHICAL ABSTRACT



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ABSTRACT

The goal of this study was to integrate a crop model, DNDC (DeNitrification-DeComposition), with life cycle assessment (LCA) and economic analysis models using a GIS-based integrated platform, ENVISION. The integrated model enables LCA practitioners to conduct integrated economic analysis and LCA on a regional scale while capturing the variability of soil emissions due to variation in regional factors during production of crops and biofuel feedstocks. In order to evaluate the integrated model, the corn-soybean cropping system in Eagle Creek Watershed, Indiana was studied and the integrated model was used to first model the soil emissions and then conduct the LCA as well as economic analysis. The results showed that the variation in soil emissions due to variation in weather is high causing some locations to be carbon sink in some years and source of CO_2 in other years. In order to test the model under different scenarios, two tillage scenarios were defined: 1) conventional tillage (CT) and 2) no tillage (NT) and analyzed with the model. The overall GHG emissions for the corn-soybean cropping system was simulated and results showed that the NT scenario resulted in lower soil GHG emissions compared to CT scenario. Moreover, global warming potential (GWP) of corn ethanol from well to pump varied between 57 and 92 g CO_2-eq./MJ while GWP under the NT system was lower than that of the CT system. The cost break-even point was calculated as \$3612.5/ha in a two year corn-soybean cropping system and the results showed that under low and medium prices for corn and soybean most of the farms did not meet the break-even point.

1. Introduction

Global temperature rose 0.6 °C during the 20th century and global temperature is estimated to increase 2–6 °C during the 21st century

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(IPCC, 2001; IPCC, 2007). Emissions of greenhouse gases (GHGs) derived from agriculture and other anthropogenic activities have been specified as one the main reasons for rising global temperature (Greenhouse Gas Working Group, 2016). Approximately 6% of all GHG emissions generated in the United States (U.S.) come from agricultural activities (EPA, 2010). These gases are in the form of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The agriculture sector could reduce GHG footprint by applying appropriate management practices; thus, agricultural fields can both sequester carbon and reduce CO_2, CH_4, and N_2O emissions (Greenhouse Gas Working Group, 2016; Pieragostini et al., 2014). Besides environmental impacts of agriculture sector, it is the major component of solving food crisis across the world; therefore, agricultural productivity is a critical factor and should be increased using proper management practices.

In order to identify proper management practices in agriculture, the basic interactions of the soil-plant-atmosphere system should be understood and the importance and effect of certain parameters such as tillage and fertilizer application rate should be estimated (Dourado-Neto et al., 1998). Modeling is an essential tool in agricultural systems science and is necessary for understanding and estimating overall agroecosystem performance (Jones et al., 2016).

Various agroecosystem models have been proposed by different studies and can be categorized in four general groups including: 1) agronomy, 2) climatology, 3) environmental and 4) environmental-agronomy models. Agronomy models focus on phenology of crops and are used to assess the efficient management for achieving higher crop yields. They usually do not consider the soil biogeochemistry and do not simulate soil emissions (Zhang et al., 2002). An example of these models is DSSAT (Jones et al., 2003). DSSAT has been in use for >20 years by researchers across the world. The model requires three sets of data encompassing crop, soil and meteorological data to simulate multi-year outcomes of crop management strategies (Hoogenboom et al., 2015). Another example of these models is the ALMANAC Simulation Model developed by the United States Department of Agriculture - Agricultural Research Service (USDA-ARS). The ALMANAC model simulates crop growth, competition, light interception by leaves, biomass accumulation, partitioning of biomass into grain, water use, nutrient uptake, and growth constraints such as water, temperature, and nutrient stress (Baez-Gonzalez et al., 2016). Climatology models mimic the interaction between different climate drivers such as impact of land surface (soil and vegetation) on the atmosphere, in order to assess the dynamics of the climate system and forecast future weather data. Physical processes of land surface (e.g. radiation, evapotranspiration) are captured by these models (Zhang et al., 2002). Environmental models focus on nutrient and element dynamics in the soil in order to simulate different soil processes such as nitrification, denitrification and decomposition.

Finally, environmental-agronomy models combine the environmental and agronomy models to simulate crop growth processes as well as soil biogeochemistry. DNDC (Li et al., 1992) and CropSyst (Stockle, 1996) are among many examples of environmental-agronomy models. Environmental-agronomy simulation models have been used at various scales from individual farms to regional scale to assess the interactions between crop, soil, atmosphere and human activities (management practices) using highly mechanistic to purely empirical approaches (Kucharik, 2003; Fumoto et al., 2008). Process-based models characterize the interactions of crop, soil and atmosphere and can be used as mechanism of understanding, estimating, predicting, and policy making (Zhang et al., 2002).

The DNDC (DeNitrification DeComposition) model was developed by Li et al. (1992) as a rain event-driven process-oriented simulation model to estimate N_2O, CO_2 and N_2 emissions from agricultural soils in the U.S. The model consists of three major submodels: soil climate, crop growth, and soil biogeochemistry. The soil climate submodel calculates moisture, temperature, and O_2 concentration in the soil based on soil characteristics and climate data. The crop growth submodel simulates crop phenological development, leaf area index (LAI), photosynthesis, respiration, assimilate allocation, rooting processes and nitrogen uptake based on the environment above and below the ground and on nitrogen (N) availability. The soil biogeochemistry submodel predicts decomposition, nitrification, denitrification, fermentation and trace gas emissions based on soil characteristics and climate data. These three submodels are interlinked such that results from the crop growth submodel is fed back into the soil climate submodel through water uptake, and is linked to the soil biogeochemistry submodel through N uptake and the supply of organic C by plants. Moreover, results from soil biogeochemistry is fed back into crop growth through its effects on N availability (Fumoto et al., 2008; Zhang et al., 2002). The original DNDC model, used by numerous researchers worldwide, has been modified and adapted to include different scenarios and other ecosystems (e.g. forests-DNDC, wetlands-DNDC, manure-DNDC) (Gilhespy et al., 2014). Several researchers have tried to evaluate the accuracy of the DNDC model in modeling the soil emissions across the world. For instance, Smith et al. (2008) employed the DNDC model for a single maize cropping system in Quebec and a wheat-maize-soybean rotation in Ontario and reported that DNDC could effectively model the overall seasonal N_2O emissions in both cases. In another effort, Sleutel et al. (2006) used the DNDC model to simulate the changes in soil organic carbon (dSOC) in northern Belgium and compared the DNDC results with a data set of 190,000 measurements carried out from 1989 to 2000. They concluded that DNDC was generally effective in estimating dSOC across the region, although accuracy varied based on soil type.

Due to an increase in the availability of high resolution spatial data modeling soil emissions across broad geographic areas has become feasible (Perlman et al., 2013; Javadnejad et al., 2017). The DNDC can be run in both site and regional and in order to simulate the soil emissions as well as crop growth in a large region, the DNDC region mode can be used. Before running the DNDC in region mode, the input data should be compiled in a database for the target region. The spatially differentiated information of location, climate, soil characteristics, crop information and farming management practices should be prepared in several Geographic Information System (GIS) files plus a climate library for each polygon or grid cell for the entire target region (DNDC, 2012). The shortcoming of the regional mode is that it cannot handle multi-year cropping systems (e.g. winter wheat-fallow-camelina). Additionally, regional mode is less flexible meaning that detailed management practices cannot be input to model. Therefore, site mode is a preferable option if we want to increase the accuracy of the model prediction. Furthermore, calibrating the model in regional mode is much harder and one study has shown that there was discrepancy between the DNDC in site mode and in regional mode (Perlman et al., 2013). In order to overcome this issue, the DNDC batch mode can be used such that a series of input files should be generated for each polygons of grid cell and run in batch mode.

ENVISION (ENVISION, 2017) is a GIS-based tool for scenario-based community and regional integrated planning and environmental assessments. It provides a robust platform for integrating a variety of spatially explicit models of landscape change processes. ENVISION is an open-source software which is adaptable to variety of geographic locations and application domains. It supports custom plug-ins which can be used for specific modeling needs. It has been developed by Bolte et al. (2007) at Oregon State University and used for numerous case studies in which the interactions of agroecosystem with human activities have been assessed (Spies et al., 2014; Turner et al., 2015).

The objective of this study was to develop and evaluate a unified interface integrating DNDC, LCA and economic analysis models within the ENVISION framework. The primary goal of this effort was to enable regional scale analysis of multi-year cropping systems considering environmental impacts and economic outcomes using a user friendly interface. The integrated framework was tested using a corn-soybean cropping system in Eagle Creek Water Shed, Indiana, USA.