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Regional scale cropland carbon budgets: Evaluating a geospatial agricultural modeling system using inventory data

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ABSTRACT

Accurate quantification and clear understanding of regional scale cropland carbon (C) cycling is critical for designing effective policies and management practices that can contribute toward stabilizing atmospheric CO_2 concentrations. However, extrapolating site-scale observations to regional scales represents a major challenge confronting the agricultural modeling community. This study introduces a novel geospatial agricultural modeling system (GAMS) exploring the integration of the mechanistic Environmental Policy Integrated Climate model, spatially-resolved data, surveyed management data, and supercomputing functions for cropland C budgets estimates. This modeling system creates spatially-explicit modeling units at a spatial resolution consistent with remotely-sensed crop identification and assigns cropping systems to each of them by geo-referencing surveyed crop management information at the county or state level. A parallel computing algorithm was also developed to facilitate the computationally intensive model runs and output post-processing and visualization. We evaluated GAMS against National Agricultural Statistics Service (NASS) reported crop yields and inventory estimated county-scale cropland C budgets averaged over 2000–2008. We observed good overall agreement, with spatial correlation of 0.89, 0.90, 0.41, and 0.87, for crop yields, Net Primary Production (NPP), Soil Organic C (SOC) change, and Net Ecosystem Exchange (NEE), respectively. However, we also detected notable differences in the magnitude of NPP and NEE, as well as in the spatial pattern of SOC change. By performing crop-specific annual comparisons, we discuss possible explanations for the discrepancies between GAMS and the inventory method, such as data requirements, representation of agroecosystem processes, completeness and accuracy of crop management data, and accuracy of crop area representation. Based on these analyses, we further discuss strategies to improve GAMS by updating input data and by designing more efficient parallel computing capability to quantitatively assess errors associated with the simulation of C budget components. The modularized design of the GAMS makes it flexible to be updated and adapted for different agricultural models so long as they require similar input data, and to be linked with socio-economic models to understand the effectiveness and implications of diverse C management practices and policies.

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1. Introduction

Agroecosystems not only provide essential life-supporting goods (e.g. food, fuel, livestock, and fiber) for humans, but also hold the promise to sequester carbon dioxide (CO_2) and other greenhouse gases (GHGs), thereby mitigating potential negative impacts of future climate change (Lal and Bruce, 1999; Paustian

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et al., 2006; Smith et al., 2007). The potential impact of changing farming practices for global emissions of GHGs has been widely recognized (UNEP, 2013). Agricultural technologies and practices can potentially mitigate ~5.5–6.0 Pg CO_2-eq yr^{-1} emissions at the global scale (Smith et al., 2007). The significant magnitude of this mitigation potential makes it necessary to consider physical, chemical, and biological dynamics of managed landscapes when understanding, quantifying, and regulating the global carbon (C) cycle (Moureaux et al., 2008; Sus et al., 2010).

The development of effective measures to stabilize atmospheric CO_2 concentration requires accurate quantification of the spatial variation and magnitude of C flux. Due to the lack of systematic and extensive collection of C budget observations, modeling approaches have been often used by researchers and decision makers (Saby et al., 2008; Ogle et al., 2010; West et al., 2010). A suite of modeling tools and methods operating at national or regional scales have been developed to estimate soil organic C (SOC) change and/or land-atmosphere C exchange by using inventory statistics, computer simulation models, satellite remote sensing products, geographic information systems, and/or eddy covariance flux tower measurements (Post et al., 2001; Whittaker et al., 2013). For example, an inventory method (West et al., 2008, 2010) was developed to estimate county-scale harvested biomass C, net primary production (NPP), SOC inputs and decomposition, and net ecosystem exchange (NEE), as well as agronomic production emissions of GHGs from seeding, tillage, fertilizer application, and harvesting. This inventory method is heavily rooted in the integration of U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) surveyed crop yields, State Soil Geographic (STATSGO) data (USDA-NRCS, 1995), and empirical relationships between SOC dynamics and diverse crop management practices derived from hundreds of field experimental sites. This data-rich and fine-scale approach has been recognized as a benchmark for cropland C budgets in several compelling model intercomparison and C budget synthesis projects, including the North American Carbon Program's (NACP) Midcontinent Mid-Continent Intensive (MCI) Campaign (Ogle and Davis, 2006; Schuh et al., 2013) and Regional Interim Synthesis (Hayes et al., 2012; Huntzinger et al., 2012). Despite the strength of the inventory approach in reliably quantifying the flux of C from ecosystems, the lack of detailed representation of the mechanisms regulating crop growth and development, water and biogeochemical cycling, and human interventions, limits its role in understanding the feedbacks among land use, climate change, and C cycling (Smith et al., 2012).

The study of complex agroecosytem relationships is best approached through process-based model analyses in combination with experimental data and field monitoring. Mechanistic agroecosystem models are being suggested as an important component of an integrated global framework for soil C monitoring and assessment (Smith et al., 2012). For example, a framework by Ogle et al. (2010) used the process-based CENTURY ecosystem model (Parton et al., 1994), operating at the monthly time step, to estimate SOC changes on the US croplands from 1990 to 2000. Their modeling system employed 121,000 National Resources Inventory (NRI) sampling sites across the US and integrated tillage practices, fertilization, soil types and edaphic characteristics, and climate variations. The point scale simulations were generalized to the scale of major land resource areas (MLRA) for reporting SOC change. The Environmental Policy Integrated Climate (EPIC) model (Williams, 1995) was tested at eighteen sites in Iowa and incorporated into a geospatial modeling system to simulate SOC change over the Iowa croplands (Causarano et al., 2008). Their modeling system used the Soil Survey Geographic (SSURGO) data that contains more detailed soil survey maps than STATSGO and a Landsat based cropland map at a resolution of 30 m, but aggregated them into a composite layer of 250 m to explicitly define EPIC modeling units. They simulated a typical corn–soybean rotation characterized with three types of tillage practices at the state-level. Their simulations were evaluated against state-level NASS surveyed corn and soybean yields. These studies consistently demonstrated the importance of using mechanistic models and highlighted the promise of using fine-scale spatial and intensive management information for accounting cropland C budgets (Smith et al., 2012).

The continuous development of spatial data for climate, terrain, crop classification, and soils has resulted in dramatic increase in spatially-explicit information, thereby providing new opportunities to further advance the application of process-based models. However, as most management data, such as tillage and fertilization, are not available in a spatially-explicit way, it is risky to assume that the performance of these models at the site level transfers to the regional scales. Recent studies (Zhang et al., 2013b, 2014) showed that C flux simulated by process-based models is sensitive to the accuracy and completeness of crop management data, as well as the resolution of soil data. In addition, process-based models demand many more parameterization and data preparation efforts than inventory approaches, rendering them prone to more sources of uncertainty. The lack of extensive evaluation of the process-based models at the regional scales makes it difficult to assess their credibility for large-scale C budget estimates, thus limiting their role in developing effective C management practices.

Our objective, therefore, was to describe and test a geospatial agricultural modeling system (GAMS) that integrates the process-based EPIC model with spatially-explicit climate, soils, land use, terrain data, and surveyed crop management data (including fertilization, tillage, planting, and harvesting) to characterize cropping systems in the US Midwest. GAMS operates at a spatial resolution of 56 m that is consistent with the recently developed Crop Data Layer (CDL) (Johnson and Mueller, 2010). GAMS contains a Geographic Information System (GIS), a proven tool for geospatial data processing and management in regional scale environmental modeling (Rao et al., 2000; Schaldach and Alcamo, 2006; Liu, 2009; Wang et al., 2010). To facilitate model implementation and results processing at such a high resolution, it is also equipped with a parallel computing component and a relational database that is compatible with multi-threading model execution, data processing, and analysis.

We selected the US Midwest as the study area to examine the performance of GAMS (Fig. 1). Agroecosystems in the Midwest provide >85%, >80%, and >50% of total maize, soybean and wheat production in the entire US (USDA-NASS, 2011) and, concomitantly provide ~60%, ~45%, and ~20% of world trade in these crops (USDA-ERS, 2010). This highly productive agricultural area is a hotspot of cropland C sequestration in the US (West et al., 2010) and contains biofuel production activities aimed at enhancing energy security and GHG mitigation (EISA, 2007; NRC, 2011; USGCRP, 2012). These dimensions combined make the US Midwest an ideal test bed for applying and assessing GAMS.

As EPIC has been extensively tested for cropland C budget simulation at the site scale (e.g. (Wang et al., 2005; He et al., 2006; Izaurralde et al., 2006; Causarano et al., 2007; Izaurralde et al., 2007; Causarano et al., 2008; Apezteguía et al., 2009; Schwalm et al., 2010; Zhang et al., 2013b)), this research focused on assessing its performance at the county-scale against NASS-surveyed harvested biomass and cropland C budgets estimated by an inventory approach (West et al., 2010). Although this inventory method has been used as a benchmark in numerous model intercomparisons and C budget syntheses, its estimates of NPP, NEE, and SOC change have not been independently corroborated at the county scale with other process-based agro-ecosystem models.

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