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Modeling state-level soil carbon emission factors under various scenarios for direct land use change associated with United States biofuel feedstock production

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ABSTRACT

Current estimates of life cycle greenhouse gas emissions of biofuels produced in the US can be improved by refining soil C emission factors (EF; C emissions per land area per year) for direct land use change associated with different biofuel feedstock scenarios. We developed a modeling framework to estimate these EFs at the state-level by utilizing remote sensing data, national statistics databases, and a surrogate model for CENTURY's soil organic C dynamics submodel (SCSOC). We estimated the forward change in soil C concentration within the 0–30 cm depth and computed the associated EFs for the 2011 to 2040 period for croplands, grasslands or pasture/hay, croplands/conservation reserve, and forests that were suited to produce any of four possible biofuel feedstock systems [corn (*Zea Mays* L)-corn, corn–corn with stover harvest, switchgrass (*Panicum virgatum* L), and miscanthus (*Miscanthus* × *giganteus Greef et Deuter*)]. Our results predict smaller losses or even modest gains in sequestration for corn based systems, particularly on existing croplands, than previous efforts and support assertions that production of perennial grasses will lead to negative emissions in most situations and that conversion of forest or established grasslands to biofuel production would likely produce net emissions. The proposed framework and use of the SCSOC provide transparency and relative simplicity that permit users to easily modify model inputs to inform biofuel feedstock production targets set forth by policy.

1. Introduction

Greenhouse gas (GHG) regulations like the California Low Carbon Fuel Standard (LCFS) and the US Environmental Protection Agency's Renewable Fuels Standard 2 (RFS2) require emissions assessment of transportation fuels based on life cycle analysis (LCA). For biofuels, life cycle GHG emissions include those from feedstock cultivation, conversion at the biorefinery, combustion in the vehicle, and land use change (LUC) prompted by increased feedstock production [1]. Both regulations rely on the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model [2] for emissions from feedstock conversion, biofuel combustion, and most aspects of feedstock production. LCFS and RFS2

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analyzes differ from GREET in their methodology of estimating GHG emissions associated with LUC. The GREET model currently includes Global Trade and Analysis Project (GTAP) model results from Purdue University [3] that estimate area and location of LUC. These values have been combined in a spreadsheet interface with an EF data set developed by the Woods Hole Research Center and various land management and policy scenarios. The LCFS had used GTAP model results combined with Woods Hole EFs before developing its own revised more detailed ecosystem-specific EF data set [4]. In the revised EF data set, Intergovernmental Panel on Climate Change (IPCC) C stock factors [5] are applied to soil C values from the Harmonized World Soil Database to derive C releases for different land use and management practices. RFS2 analyzes currently employ a combination of the Forest and Agricultural Sector Optimization Model (FASOM) (Texas A&M University) to assess domestic LUC and the Food and Agricultural Policy Research Institute (FAPRI) model (Iowa State University) to estimate indirect international LUC. Direct soil C EFs are informed by the CENTURY soil organic matter (SOM) model [6].

To date the EFs being incorporated into LCA have been largely developed at the coarse (i.e. national and regional) scale. The averaging effects resulting from this coarser scale resolution are known to create high levels of uncertainty in estimates of soil C stock change thereby introducing uncertainty into biofuel LCA results [7]. The development of spatially-explicit modeling frameworks can improve the accuracy of biofuel assessments [8]. To accurately predict changes in soil C stocks resulting from LUC, assessments must consider initial soil C content, cultivation practices, fertilizer inputs and climate [9,10]. To simulate the forward trajectory of soil C stock changes with process models one must properly estimate soil C levels and their distribution among three kinetically defined pools [6]. Process models like CENTURY account for key historical and spatial detail and should be of great value when incorporated into LCA frameworks. CENTURY modeling, however, has several aspects that can significantly influence results and therefore merit attention. First, work by Ogle et al. [11] and Kwon and Hudson [12] suggests that simple reconstruction of land use history to estimate initial soil C content at the time of LUC may not be sufficient and indicates that key coefficients used in CENTURY may not accurately predict the effects of cultivation and fertilizer application on C decay rates. Calibration of model coefficients describing decay interactions may be needed to improve EF accuracy. This calibration should be easier for corn-based biofuel scenarios as there are far more relevant data available for these systems than for advanced biofuel systems. Second, feedstock yield and production practices may deserve particular attention as they have a large impact on soil C. Further, the characteristics of perennial biofuels (e.g. yield) that influence soil C stocks are likely to change rapidly with crop improvement. Values used for these parameters in CENTURY modeling should be routinely revisited as energy crop technology advances.

Given that finer resolution soil C EFs will benefit estimates of LUC GHG emissions associated with biofuel production, we developed a modeling framework for the conterminous US to generate state-level soil C EFs for the 0–30 cm soil depth. Scenarios were developed for the period of 2011–2040 where four present land uses (croplands, grasslands or pasture/hay, croplands/conservation reserve, and forests) could be converted to four possible biofuel feedstock production systems [corn (*Zea Mays* L)-corn, corn–corn with stover harvest, switchgrass (*Panicum virgatum* L), and miscanthus (*Miscanthus × giganteus Greef et Deuter*)]. We predicted EFs by running various scenarios, followed by evaluation of important assumptions made during simulations – by allowing an increase in corn productivity due to improving technology and acceleration in soil C decay due to cultivation and fertilization under corn-based agriculture.

2. Materials and methods

2.1. *Modeling framework for US soil C emission factors*

2.1.1. *Land use change scenarios*

A suite of LUC scenarios were developed with the assumption that land presently in croplands, grasslands or pasture/hay (here-to-for referred to as grasslands), and forests could be converted to at least one of four likely biofuel feedstock production systems (corn–corn, or corn–corn with stover harvest, switchgrass, and miscanthus). To anticipate emissions from agricultural lands previously set aside for conservation, croplands/conservation reserve scenarios considered lands that had never been cropped (grasslands) and that had reverted to grasslands after a period of cropping.

Corn-based systems were simulated under three different tillage options [i.e. conventional tillage (CT), reduced tillage (RT), and no tillage (NT)] while the two perennial grass systems were simulated under NT. While these terms are notably vague and vary regionally, they differ in disturbance intensity and the depth of residue burial. We assumed that the fraction of aboveground residue/biomass transferred to soils was 0.95, 0.7, and 0.05 for CT, RT, and NT respectively. The stover harvest rate was set at either 0 or 30% to limit soil erosion and maintain soil fertility [13,14]. Biomass harvest rates for switchgrass and miscanthus were set as 80 and 90% of their peak harvestable biomasses, respectively, which are attained in late summer. These combinations resulted in a total of 32 general LUC scenarios to consider (Table 1). While harvest rates are less well established for miscanthus, higher harvest rates can be justified because its biomass, and thus the amount of residues returned to soil with these harvest rates, can be twice that achieved by switchgrass systems. Actual harvest rates may be lower due to losses incurred before harvest which is typically conducted after senescence and associated nutrient remobilization have occurred [15,16]. To evaluate the effect of such harvest loss, we conducted runs at a 70% harvest rate for miscanthus.

2.1.2. *States suitable for land use change scenarios*

To estimate state-level soil C EFs associated with likely LUC scenarios we sought to identify states with land well suited for any of the proposed bioenergy cropping systems. We used the 2010 Cropland Data Layer (CDL) [17], which combines remote sensing imagery and US Department of Agriculture (USDA)-National Agricultural Statistics Service (NASS) survey data to

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