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Time effects of climate change mitigation strategies for second generation biofuels and co-products with temporary carbon storage

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ABSTRACT

Second generation biofuels offer a means of reducing greenhouse gas emissions and storing or delaying soil carbon emissions relative to petroleum-based fuels depending upon the strategy used to synthesize the biofuel and co-products. Unless mitigated, the soil organic carbon and nitrogen loss resulting from removing agricultural residues for biofuel production may cause life cycle greenhouse gas emissions to surpass national policy thresholds, and thus risk non-compliance with renewable fuel policy. Strategies to mitigate soil organic carbon loss such as using nutrient and carbon-rich, and stable land amendments will lead to time-variable greenhouse gas credits. Recent studies have argued for using time-dependent rather than time-averaged radiative forcing methods for biofuel greenhouse gas accounting but few life cycle assessment studies have examined the impact of time-varying emissions of soil organic carbon using the Intergovernmental Panel on Climate Change tier 3 models. This study applies a time-dependent radiative forcing approach to a 100-year time-series data set of life cycle greenhouse gas emissions for lignocellulosic ethanol that includes temporally variable soil greenhouse gas emissions. This study demonstrates that averaging soil emissions and neglecting the time when the sequestration or release occurs within a selected time horizon can lead to a 9% to over 80% overestimation of the magnitude of the effect of the mitigation strategy. This affirms that employing strategies to maintain soil organic carbon stock early within a biofuel program supports climate change mitigation. Such strategies would guide farmers to best manage soil carbon within the biofuel production life cycle. Time-dependent approaches underscore the need for early measures of greenhouse gas curtailment to support sustainable renewable biofuel and agricultural policy.

1. Introduction

Second-generation biofuels, produced from agricultural residues, are under development to meet energy security objectives and to mitigate the climate change risks associated with petroleum-based transportation fuels (Eisentraut, 2010). Recent U.S. policies and regulations require these fuels to have 60% lower greenhouse gas (GHG) emissions compared to petroleum counter-products (U.S.Congress, 2007). However, managing agricultural residue collection to maintain soil carbon stock while harvesting biomass for biofuels is critical for making such mitigation strategies sustainable (Sathre and Gustavsson, 2011; Wilhelm et al., 2007). Crop residues are sources of carbon and nutrients for soil and harvesting them changes the soil carbon stock (Petersen et al., 2013) and availability of nutrients such as nitrogen. Soil carbon stock changes over time due to land use history (e.g. intensive farming), biogeochemistry of soil and because of management practices such as removing crop residues, and imbalanced use of fertilizers and tillage (Kim et al., 2009). Besides nutrient depletion, removing crop residues may accelerate soil degradation and potentially reduce crop yield (Wiloso et al., 2014). Soil GHG emissions vary in time because of factors, such as local climate and soil texture class influence on carbon and nitrogen residence times in the soil. The unique and variable GHG emissions and carbon sequestration profiles of the land under crop production for biofuel, contribute to temporally variable life-cycle GHG emissions of these fuels over time (Pourhashem et al., 2013a). Since biofuels have temporally unique GHG emission profiles because of their

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feedstock of origin, comparing the effectiveness of alternative production pathways could be prone to error if time effects are neglected (Gustavsson and Sathre, 2011). This paper focuses on the time effects of biofuels produced from agricultural residues, with specific examination of soil C and N flux arising from agricultural residue management. The results of this study have important implications for planning co-product design as well as effective biofuel and agricultural policies.

1.1. Time horizon and carbon accounting

Life-cycle GHG emissions from fossil fuel production and combustion cycles tend to be constant or predictable over time considering the maturity of the technology. Fossil fuels are produced in existing commercial facilities and their production and consumption cycles tend to follow market demand. A biofuel's net life-cycle GHG emissions, however, vary in time because of the feedstock's production cycle. Biomass production and harvesting contribute to time variable GHG emissions from agricultural soils due to time-lags in C and N fluxes. Therefore, choosing a time horizon (TH) that covers all significant bioenergy system activities, and provides sufficient time to account for the GHG fluxes that incur time-lags is very critical for fairly comparing alternative biofuel and transportation systems. Life Cycle Assessment (LCA) studies from literature have used multiple THs. For example, Fargione et al. (2008) used a 50-year TH to track the decay time of GHG emissions related to land use change (LUC) within forestry timber byproducts. Searchinger et al. (2008) used a 30 year TH based on the critical periods for avoiding irreversible adverse effects from climate change (Forster et al., 2007). Both studies use a 100-year global warming potential (GWP) approach, but neither evaluated the time-dependency of individual GHG gas release as Edwards and Trancik (2014) argue is needed for climate stabilization, nor did either examine the effect of TH sensitivity to account for time-delayed soil GHG emissions.

Early studies that had treated large one-time LUC emissions spikes (e.g., Searchinger et al., 2008) used straight-line amortization to partition GHG emissions over a defined TH. This approach gives an equal weighting to all GHG emissions regardless of the time of each gas's release by spreading them over the chosen TH, equivalent to assuming a 0% discount rate for emissions. Whereas a number of researchers (McKechnie and MacLean, 2013; O'Hare et al., 2009) have argued against using economic discounting for treating irregular carbon emissions in time for biofuel systems. They and others (Cherubini et al., 2013; Kendall et al., 2009; Levasseur et al., 2010) have proposed using kinetic decay relationships to track the time-dependence of bioenergy-related life-cycle GHG emissions in the atmosphere. To account for emission timing, the authors use cumulative radiative forcing (CRF) functions as alternatives to the 100-year global warming potential (GWP) and propose methods such as dynamic LCA (Levasseur et al., 2012) or time-adjusted warming potentials (TAWPs) (Kendall, 2012). While most of these studies address the critical issue of GHG emissions timing, they rely on a set TH and do not analyze impacts beyond that period. O'Hare et al. (2009) consider post-cultivation practices of maize bioenergy systems where land partially returns to its original condition by averaging annual CO_2 sequestration. Holma et al. (2013) and Petersen et al. (2013) discuss the importance of including the soil carbon change in bioenergy life-cycle carbon accounting as they happen or stabilize over a long period of time. Thus, to compare the life-cycle performance of biofuel production systems it is important to explore the post-biofuel production soil carbon effects and to do so using a biogeochemical model capable of tracking C and N flux in time. Despite the significant body of literature on LCA of second-generation biofuels (Karlsson et al., 2014), there has not been enough research that investigates the impact of variable emissions from feedstock production in these studies.

The objective of this paper is to study whether time-varying soil carbon loss and storage as well as N_2O and CH_4 emissions should be considered in biofuel life-cycle GHG accounting, when SOC is managed, to support policy decision-making. To test this, a biogeochemical model (DayCent) is used to generate annual soil CO_2, N_2O, and CH_4 emissions combined with biofuel production and combustion life-cycle GHG emissions. A time-dependent radiative forcing (RF) model is applied to compare the temporal patterns of GHG emissions for two alternative bioethanol scenarios. The scenarios compare alternative lignin co-product uses within the life cycle of lignocellulosic ethanol; where 1) the carbon rich lignin co-product is stored as biogenic carbon; and 2) the co-product is combusted to recover energy. Prior research (Adler et al., 2014; Pourhashem et al., 2013a) examined time-averaged soil CO_2 and N_2O emissions over a 20-year ethanol production time horizon (i.e., using straight-line amortization with zero discounting) with the standard 100-year GWP accounting framework. The aim of this research is to investigate whether accounting for emissions timing in scenarios of land management, is significantly different from considering the time-averaged 100-year GWP for 20 years of biofuel production.

2. Methods

This section provides details on the scope and framework and boundary conditions of the study as well as the description of the GHG accounting model employed.

2.1. Framework and goal

This study examines two bioethanol production scenarios with alternative co-product designs using a time-dependent GHG accounting approach. The analysis investigates the effect of a 100 and 20-year residue harvest for biorefinery operation over a 100-year timeframe. In the latter case, the 20-year period is followed by an 80-year period where biofuel production stops and residue is not collected for any application (Table 1). Life-cycle GHG emissions of bioethanol production and use over 20 and 100-years are compared with gasoline production and use over the same timeframes. Annual life-cycle GHG emissions of gasoline (on a per MJ basis) are assumed not to vary annually. All scenarios are compared to a baseline crop cultivation scenario where the crop residue is not collected for any purpose (Table 1). Two main lignocellulosic ethanol production options from crop residue (corn stover, and wheat and barley straw) and the associated life-cycle emissions have been adopted from Pourhashem et al. (2013a). They examined the GHG emission tradeoffs of using the lignin-portion of the agricultural residue for energy recovery or for soil organic carbon (SOC) management through amending the lignin-portion to land. In the latter co-product option, the negative effects of soil loss due to crop residue removal (Blanco-Canqui and Lal, 2009; Cherubini and Ulgiati, 2010; Lal, 2008; Liska et al., 2014) are mitigated (Adler et al., 2014) through amending the soil with the carbon-rich and stable high lignin fermentation by-product (HLFB) derived from fermentative biofuel conversion (Johnson et al., 2004) systems that only use fermentable sugars from the biomass for alcohol production [see, Spatari et al., 2010]. On the other hand, the energy value of the lignin can be utilized through direct combustion (combined heat and power, CHP) or cofired at a coal-fired power plant. This previous study showed that amending agricultural soils with lignin improves the environmental and economic performance over using it as an energy source (Pourhashem et al., 2013a).