Global Environmental Change 35 (2015) 269–278

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

The dynamic soil organic carbon mitigation potential of European cropland

Stefan Frank[a,*], Erwin Schmid[b], Petr Havlík[a], Uwe A. Schneider[c], Hannes Böttcher[d], Juraj Balkovič[a,e], Michael Obersteiner[a]

[a] International Institute for Applied Systems Analysis, Laxenburg, Austria
[b] University of Natural Resources and Life Sciences, Vienna, Austria
[c] University of Hamburg – KlimaCampus, Hamburg, Germany
[d] Öko-Institut, Berlin, Germany
[e] Department of Soil Science, Comenius University in Bratislava, Bratislava, Slovak Republic

ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form 6 August 2015
Accepted 12 August 2015
Available online xxx

Keywords:
Partial equilibrium
GHG emissions
Land use modeling
Conservation tillage
Soil carbon
Dynamics

ABSTRACT

Changes in soil organic carbon stocks depend on the management regime and a variety of environmental factors including climatic conditions and soil properties. So far, the dynamics of soil organic carbon have not been explicitly represented in global economic land use optimization models. Here, we apply an approach to represent soil organic carbon dynamics explicitly in a global bottom-up recursive dynamic partial equilibrium model using carbon response functions simulated with a biophysical process-based model. We project soil organic carbon emissions from European cropland to decrease by 40% from 64 $MtCO_2$ in 2010 to about 39 $MtCO_2$ in 2050 mainly due to saturation effect when soils converge toward their equilibrium after management, crop rotation, or land use change. Moreover, we estimate a soil organic carbon mitigation potential for European cropland between 9 and 38 $MtCO_2$ per year until 2050 for carbon prices between 10 and 100 USD/tCO_2. The total European mitigation potential including co-benefits from the crop and livestock sector due to the carbon price is even higher with 60 $MtCO_2$ equivalents (eq) per year. Thus carbon sequestration in soils could compensate 7% of total emissions from agriculture within the EU, 10% when including co-benefits from the crop and livestock sector. However, as production is reallocated outside Europe with increasing carbon prices, emissions decrease in Europe but increase in the rest of the world (20 $MtCO_2$ eq). Preventing GHG emission leakage to the rest of the world would decrease the European soil organic carbon mitigation potential by around 9% and the total European mitigation potential including co-benefits by 16%. Nevertheless, the net global mitigation potential would still increase. We conclude that no significant contributions to emission reduction targets should be expected from the European cropland carbon sequestration options considered in this study.

1. Introduction

World soils are the third largest global carbon stock behind the oceanic and the geologic carbon pool. They contain about twice as much organic carbon as the atmosphere and thrice as much as biomass (Powlson et al., 2011b; Smith, 2012b). Soils can be a major source or sink of carbon dioxide (CO_2) emissions depending on the land use and management regime. It has been estimated that agricultural ecosystems have lost 25–75% of their original soil organic carbon (SOC) pool due to the conversion of natural to agricultural ecosystems and other soil degradation processes such as erosion, salinization, and nutrient depletion (Lal, 2011). Improved management of agricultural land has the potential to both reduce net greenhouse gas (GHG) emissions and to serve as a direct carbon sink through SOC sequestration. Management practices such as reduced and minimum tillage, improved residue management and crop rotations as well as the conversion of marginal cropland to native vegetation or conversion of cultivated land to permanent grassland offer the potential to increase SOC stocks (IPCC, 2007). However, sequestration rates do not only depend on the management regime but also on environmental factors including climatic conditions and soil properties (Bellamy et al., 2005). Depending on the history of land management, different management systems may either sequester carbon in the

---

[*] Corresponding author at: Schlossplatz 1, A-2361 Laxenburg, Austria.
E-mail address: frank@iiasa.ac.at (S. Frank).

http://dx.doi.org/10.1016/j.gloenvcha.2015.08.004
0959-3780/

soil or cause emissions (West et al., 2004). Moreover, SOC stocks usually increase as mean annual temperature decreases, and rainfall and clay content increase due to reduced decomposition rates (Post et al., 1982; Powlson et al., 2011a).

While the dynamic interactions between SOC sequestration rates and soil management are widely acknowledged in literature, they have not been considered in most existing economic land use models. A major obstacle is the high data and computing requirements for an explicit representation of alternative land use sequences since a model has to be able to track all different management choices and paths (Schneider, 2007). Several studies estimated SOC emissions from arable land and mitigation potential at regional and global level using either biophysical SOC models in combination with current land use or projections of land use and land use change (Lugato et al., 2014; Smith et al., 2005a; Vleeshouwers and Verhagen, 2002; Yu et al., 2013; Zaehle et al., 2007) or land use models with static SOC sequestration rates (De Cara and Jayet, 2006; Schulp et al., 2008; Thomson et al., 2008). Most studies conclude that European SOC mitigation potential could contribute significantly in reaching emissions saving targets even though estimates have been revised downward (Smith et al., 2005b).

While the technical potential (full adoption given biophysical constraints) of conservation tillage may be large (0.37–0.92 tCO_2/ha and year, see Aertsens et al. (2013) and Vleeshouwers and Verhagen (2002)), economic mitigation (adoption under a given carbon price) potentials are often smaller. Freibauer et al. (2004) identify the carbon sequestration potential for the EU15 to be around 59–70 $MtCO_2$ per year with the most promising measures being improved cropland and grassland management (e.g. increased organic matter input, reduced tillage). De Cara and Jayet (2006) quantify the economic mitigation potential of conservation tillage in EU15 to be around 8 $MtCO_2$ at a carbon price of 20 Euro/tCO_2 (27 $MtCO_2$ with 100 Euro/tCO_2). Recently, the PICCMAT project (Piccmat, 2008) estimated the carbon mitigation potential for reduced and minimum tillage of around 10 and 20 $MtCO_2$ respectively for EU27.

Despite the variety of studies, large uncertainties in the magnitude of SOC emissions and mitigation potential prevail. Recent studies questioned the feasibility to achieve high emission savings through soil organic carbon sequestration (Powlson et al., 2011b). Uncertainties can be attributed to gaps in the understanding of future land use change, quantification of the response of carbon sequestration to land use change (Schulp et al., 2008), future level of adoption of mitigation measures, potential feedback on N_2O and CH_4 emissions, and persistence of mitigation (Smith, 2012b). In addition, there is an ongoing debate about the "genuinely" positive effect of conservation tillage on SOC sequestration and consequently climate change mitigation since most existing studies relied on shallow sampling depth when comparing sequestration rates of conservation and conventional tillage systems. Some studies conclude that even though conservation tillage may increase surface SOC concentrations, it does not store more SOC in the overall soil profile but solely redistributes carbon in the soil (Baker et al., 2007; Luo et al., 2010).

Besides biophysical uncertainties also economic effects such as GHG emission leakage need to be considered to guarantee effectiveness of GHG mitigation options and climate change policies (Ostwald and Henders, 2014). In the European Union (EU), CO_2 emissions from agriculture, forestry and other land use have not been included in the emissions reduction targets so far besides the CO_2 emissions due to energy use. This is under discussion in the forthcoming energy and climate mitigation policy framework for 2030 to ensure cost-effective GHG abatement across sectors (EC, 2014). However, applying a mitigation policy only at regional scale may result in emission leakage to regions not adopting the mitigation policy (IPCC, 2000). Indirect effects such as conversion of native vegetation elsewhere to agriculture in order to compensate for agricultural production losses (e.g. through switch to perennial crops for biofuel production or decreased productivity related to the adoption of conservation tillage) could therefore negate the benefits of carbon sequestration through increases in GHG emissions in other sectors or regions (Powlson et al., 2011b; Smith, 2012b).

To reduce uncertainty and provide theoretically and empirically more consistent estimates of the European SOC mitigation potential from cropland, a framework is needed capable of representing biophysical SOC dynamics as well as the land use and land use change sector including its economic drivers and feedbacks to and from other sectors. Hence, we implement a dynamic SOC modeling approach introduced by Schneider (2007) and applied so far only in a case study region (Freier et al., 2011) into GLOBIOM-EU, a global bottom-up partial equilibrium model based on GLOBIOM (Global Biosphere Management Model) (Havlík et al., 2014). We estimate SOC emissions from cropland in the EU until 2050. Then we assess the dynamic European cropland SOC mitigation potential by implementing a carbon price in the model. By mimicking a policy implementation in Europe only, we assess potential GHG emission leakage effects in the rest of the world (ROW). In addition, we explore the impact of preventing emission leakage on the European SOC mitigation potential.

2. Methodology

We use GLOBIOM-EU, a partial equilibrium land use model based on GLOBIOM (Havlík et al., 2014). GLOBIOM-EU and GLOBIOM are identical regarding data sets and modeling approach for regions outside Europe. Inside Europe, GLOBIOM-EU has been refined to allow for a more detailed representation of the EU28 member countries. Here we provide details about the model in general, spatial resolution, data sources, and the improved crop sector representation in Europe. Moreover, we describe the implementation of SOC dynamics in the model and the scenarios.

2.1. GLOBIOM-EU

GLOBIOM-EU is the European variant of the Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2014) which has been used in several European assessments (EC, 2013, 2014). It is a global partial equilibrium model integrating the agricultural, bioenergy, and forestry sectors. A global agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus subject to resource, technological, demand, and policy constraints similar to McCarl and Spreen (1980). Demand for final products and international trade is represented at the level of 57 aggregated world regions (28 EU member countries, 29 regions outside Europe). Commodity demand is specified as stepwise linearized downward sloped function with constant own-price elasticities following Schneider et al. (2007) parameterized using FAOSTAT data on prices and quantities, and price elasticities as reported by Muhammad et al., (2011). Outside Europe the supply side of the model is based on a detailed disaggregation of land into Simulation Units (SimUs)—clusters of 5 arcmin pixels belonging to the same country, altitude, slope, and soil class, and to the same 0.5° × 0.5° pixel (Skalský et al., 2008). For EU input data sets (except Croatia, Cyprus, and Malta) a more detailed SimU architecture (Balkovic et al., 2009) is used (i.e. basic spatial unit is a 1 × 1 km pixel, six altitude and seven slope classes, soil classes are characterized by soil texture compositions, depth, and coarse fragment content, NUTS2 regions boundaries plus additional dimensions for land cover category, presence of irrigation equipment, and river catchment reference). Information on land