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The contribution of future agricultural trends in the US Midwest to global climate change mitigation

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ABSTRACT

Land use change is a complex response to changing environmental and socioeconomic systems. Historical drivers of land use change include changes in the natural resource availability of a region, changes in economic conditions for production of certain products and changing policies. Most recently, introduction of policy incentives for biofuel production have influenced land use change in the US Midwest, leading to concerns that bioenergy production systems may compete with food production and land conservation. Here we explore how land use may be impacted by future climate mitigation measures by nesting a high resolution agricultural model (EPIC – Environmental Policy Indicator Climate) for the US Midwest within a global integrated assessment model (GCAM – Global Change Assessment Model). This approach is designed to provide greater spatial resolution and detailed agricultural practice information by focusing on the climate mitigation potential of agriculture and land use in a specific region, while retaining the global economic context necessary to understand the far ranging effects of climate mitigation targets. We find that until the simulated carbon prices are very high, the US Midwest has a comparative advantage in producing traditional food and feed crops over bioenergy crops. Overall, the model responds to multiple pressures by adopting a mix of future responses. We also find that the GCAM model is capable of simulations at multiple spatial scales and agricultural technology resolution, which provides the capability to examine regional response to global policy and economic conditions in the context of climate mitigation.

1. Introduction and background

Land use decision making occurs at local and regional scales in response to many driving forces, including both location specific environmental conditions and national and global economic and policy incentives. In the US Midwest and Great Plains states, land use change has historically been driven by agricultural prices and policies, including international commodity market prices, crop subsidies and national conservation programs (Sylvester et al., 2013). In the past decade, the emergence of policies that encourage development of biofuels and, consequently, agricultural-land use patterns have prompted research into how such policies might not only influence global land use change and emissions (Searchinger et al., 2008; Mosnier et al., 2013) but also how such land conversions could be sustainably achieved (Robertson et al., 2008; Gelfand et al., 2013). Such approaches have focused either on large scale land use patterns and the global effects or, conversely, small scale regional land use change drivers and consequences. While there is increasing awareness of the connectedness between local land use and global drivers, less is understood about these interactions (Meyfroidt et al., 2013).

A range of modeling approaches have been used to explore potential future land use change in response to changes in crop productivity, land management, agricultural economics and regional to global policy instruments. Integrated assessment models that combine detailed representations of energy systems and land use systems in a global economic framework are one tool used for insight into integrated land-use mitigation potentials (Wise et al., 2009; Reilly et al., 2013). However, they are typically driven by historical aggregate statistics of production in combination with exogenous assumptions of future trends in agricultural productivity; most such global integrated models do not currently explore alternative agricultural management practices relevant for climate adaptation or greenhouse gas emissions mitigation. These global models can provide valuable insights. For example, a global economic incentive to expand forest land does not ensure that all

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regions of the world will experience significant afforestation – there are many tradeoffs and some regions may benefit by producing more food to export to the afforesting regions (Thomson et al., 2010). However these models typically must operate at relatively coarse scale spatial resolution and without too much detail in any one economic sector in order to be computationally efficient. And, while there are agricultural models capable of detailed biophysical modeling of farm management and climate impacts on crop yield, soil erosion and carbon and greenhouse gas emissions (Zhang et al., 2010), these are typically applied at spatial scales that are incompatible with the coarser resolution employed in integrated assessment modeling.

More recently, multi-model and integrated model approaches that can explore the interactions between biophysical land productivity and management, and larger scale socioeconomic drivers have been developed (Sands and Edmonds, 2005; Godfray et al., 2011). Agro-ecosystem models at relatively high resolution have been coupled to regional economic models to investigate specific questions such as potential biofuel supply (Schonhart et al., 2010; Egbendewe-Mondzozo et al., 2011); alternatively, economic model simulations may be limited to specific geographical regions (Van Delden et al., 2011; Rutledge et al., 2008). While these regionally focused integrated approaches can incorporate boundary conditions on economics, policy, and climate, the future decisions made within the region of interest cannot account for how other world regions are responding to those external pressures.

Meanwhile global-scale integrated tools have also emerged, combining crop models that can be applied globally using an aggregate solution of designating homogeneous modeling units based on environmental conditions (Liu et al., 2007; Liu and Yang, 2010). The agro-economic model GLOBIOM has made use of this ability in a global agricultural economics model that uses an agro-ecosystem model to inform crop productivity (Havlik et al., 2011; Schneider et al., 2011). This type of model integration is complicated by the different spatial resolutions of the different model types. Global integrated assessment models typically operate at coarse spatial scales and resolve on political boundaries, while within these boundaries environmental conditions for crop production (i.e. soils, topography, and weather) can exhibit high spatial variability. Van Delden et al. (2011) rightly point out that appropriate scaling and coupling of these model systems should be carefully constructed based on the intended use of model outcomes. A recent review of current approaches highlights the need for greater integration between biophysical and economic sectors and across scales to capture the dynamics of distant drivers of land use change (Meyfroidt et al., 2013).

Here we explore the potential for these interactions by nesting a high-resolution agricultural model for the US Midwest within a global integrated assessment model. This approach is designed to provide greater spatial resolution and detailed agricultural practice information by focusing on the climate mitigation potential of agriculture and land use in a specific region, while retaining the global economic context necessary to understand the far ranging effects of a climate mitigation targets. Our framework is the Global Change Assessment Model (GCAM) (Kim et al., 2006; Clarke et al., 2007), modified for this study in order to increase spatial and agricultural technology detail for the US Midwest (GCAM-MidwestUS-AgLU). While scientific studies of emissions mitigation from land use activities in this region have focused on the potential expansion of bioenergy cropping (Gelfand et al., 2013), stakeholders are also interested in information on additional questions including the use of alternative cropping systems and potential for carbon sequestration through afforestation (Rice et al., 2012). To inform these questions in greater detail, we use EPIC (Williams, 1995; Izaurralde et al., 2006), a process-based agro-ecosystem model, to provide GCAM with different crop management and bioenergy crop options identified as potential climate change mitigation strategies. GCAM is then run globally under a no policy future and under two scenarios of climate mitigation that follow the radiative forcing targets of the Representative Concentration Pathways (Moss et al., 2010; van Vuuren et al., 2011). The resulting runs are evaluated to explore possible future land use change in the US Midwest as a result of global climate mitigation policies.

2. Methods

2.1. The Global Change Assessment Model (GCAM)

GCAM is a global integrated assessment model of human activities that contribute to greenhouse gas emissions (Kim et al., 2006; Clarke et al., 2007). Originating as an energy-economy model, it contains highly detailed representation of energy systems and technologies and it also includes a fully integrated representation of land use and agriculture (Wise and Calvin, 2011). GCAM typically operates for 14 global regions delineated based on political boundaries (countries, group of countries), and 151 agro-ecological zone (AEZ) subregions for agriculture and land use based on the classification by Monfreda et al. (2009). The model calibrates to a 2005 base year and projects human activities forward to 2095 in 5 year time steps, solving for equilibria in all energy, agriculture, and greenhouse gas emissions markets simultaneously. Thus, its strength is in discerning long-term trends and interactions between energy, land, atmosphere and economy. The future model projections are driven by external inputs of population growth and economic growth (GDP) in a standard No Policy case. GCAM simulates detailed technological development in the energy system including development and deployment of renewable energy (wind, solar, hydropower, geothermal, bioenergy) as well as alternatives such as nuclear energy and new technological developments such as carbon capture and storage from power plants and industry. Standard GCAM treatment of agricultural sector technology development relies on an FAO projection of crop yield increases out to 2050 (Briunsma, 2009; Kyle et al., 2011) that is based on historical trends of yield, and future assumptions about both management developments and crop genetic improvements.

GCAM is also run with climate policy targets, and institutes prices on carbon to limit greenhouse gas emissions or atmospheric radiative forcing to specific targets. In this study, we simulated a No Policy case and two climate policy options that limit atmospheric radiation to 4.5 $W m^{-2}$ (Mitigation – 4.5) and 2.6 $W m^{-2}$ (Mitigation – 2.6) in the atmosphere in 2100. The mitigation cases include a carbon tax on all carbon emissions, regardless of source. Thus, land use change emissions are taxed equal to emissions from fossil fuel combustion. This results in strong incentives to preserve terrestrial carbon through forest preservation and afforestation, and through intensification of agricultural systems to avoid cropland expansion, while still producing cellulosic material for bioenergy production through crops and residues (Wise et al., 2009; Thomson et al., 2011). This tax values carbon both in vegetation and soils.

2.1.1. Parameterization of GCAM to represent the US Midwest region

For this study, additional data were needed to calibrate GCAM with a higher spatial resolution for the US Midwest and to parameterize specific crop management options. GCAM typically operates with 151 sub-regions globally for agriculture and land use, with 10 of those located in the United States. We established a higher resolution set of subregions nested within the global model.