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What are the effects of Agro-Ecological Zones and land use region boundaries on land resource projection using the Global Change Assessment Model?

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Understanding potential impacts of climate change is complicated by spatially mismatched land representations between gridded datasets and models, and land use models with larger regions defined by geopolitical and/or biophysical criteria. Here we quantify the sensitivity of Global Change Assessment Model (GCAM) outputs to the delineation of Agro-Ecological Zones (AEZs), which are normally based on historical (1961–1990) climate. We reconstruct GCAM's land regions using projected (2071–2100) climate, and find large differences in estimated future land use that correspond with differences in agricultural commodity prices and production volumes. Importantly, historically delineated AEZs experience spatially heterogeneous climate impacts over time, and do not necessarily provide more homogenous initial land productivity than projected AEZs. We conclude that non-climatic criteria for land use region delineation are likely preferable for modeling land use change in the context of climate change, and that uncertainty associated with land delineation needs to be quantified.

1. Introduction

Global climate projections rely on a scenario-based process by which Integrated Assessment Models (IAMs) generate estimates of anthropogenic emissions and spatially explicit land use change for driving global climate and Earth System Models (ESMs) (Moss et al., 2010; Taylor et al., 2012; van Vuuren et al., 2013). These projections are used in turn to estimate impacts of global change on a wide variety of human and environmental systems. Climate change in the upcoming century is expected to substantially change conditions at local and regional scales, but current assessments indicate a high degree of variability in impact direction and magnitude across models, regions, and sectors (IPCC, 2014a). Some of this variability may be due to uncertainty in regional climate projections. For example, recent studies have highlighted large spreads in regional multi-model climate ensemble projections, at both coarse and fine resolutions (e.g., Mearns et al., 2013; Qiao et al., 2014; van der Linden and Mitchell, 2009). While these differences are often attributed to model differences in general, inappropriate resolution or spatial aggregation in models can cause significant biases in outputs (Di Vittorio and Miller, 2014; Ogle et al., 2006; Riley et al., 2009).

Unfortunately, uncertainties associated with a given spatial delineation of the earth are not usually accounted for in modeling studies because models are often constructed at only a single resolution or level of aggregation, or because it is too computationally expensive to rerun simulations using different spatial configurations. Errors associated with a given spatial delineation are compounded when different models interact, as is the case in scenario-based global climate projections. Where IAMs often delineate the earth based on geopolitical and biophysical factors, ESMs generally use a regular grid at coarse resolution, and impact models usually have fine resolution with either regular or irregular grids. Not only are the spatial units different between models, but the types and definitions of land use and cover are different as well. These fundamental discrepancies and associated inconsistencies in the IAM-ESM-impact chain can render projections of local and regional climate change and impacts invalid, and in some cases cause ESMs

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to simulate an entirely different scenario from the one prescribed by the IAM (Di Vittorio et al., 2014).

Four IAMs, each with a different spatial delineation of the land surface, generated the four Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011a) used by ESMs in phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). RCP class IAMs are economic models that project detailed breakdowns of the production and use of energy and land resources, balancing supplies and demands of modeled commodities through market mechanisms. A key feature of these IAMs is that they include a biogeophysical component that estimates climate change associated with projected energy and land resource utilization. This interaction between the human and environmental components is critical for generating the RCP scenarios, which are based on specific climate targets (van Vuuren et al., 2011a), although climate impacts are not fed back into energy and land projections. Incorporating the climate-land feedbacks using mechanistic ecosystem models is a relatively new area of research (Calvin et al., 2013; Di Vittorio et al., 2014; Kicklighter et al., 2014; Kyle et al., 2014; Reilly et al., 2012) and has the potential to introduce additional uncertainty associated with model spatial delineations.

For CMIP5, each IAM calculated land use for a different set of geopolitical regions, and these outputs were harmonized to historical data by a separate model with its own unique representation of land use. The four IAM models contain the following numbers of regions: 11 (MESSAGE, Riahi et al., 2011), 14 (GCAM, Thomson et al., 2011), 24 (AIM, Masui et al., 2011), and 26 (IMAGE, van Vuuren et al., 2011b). Three models (AIM, MESSAGE, IMAGE) incorporated downscaling to a half-degree grid, with MESSAGE and IMAGE using historical Agro-Ecological Zone (AEZ) data to inform the downscaling. The individual model outputs were harmonized (and downscaled in the case of GCAM) by the Global Land-use Model (GLM) to a half-degree global grid (Hurtt et al., 2011), and then passed to ESMs. GLM employs local spatial relationships, but as a global model it still lacks local constraints such as barriers to land availability, limits to intensification, (in)accessibility to markets, restrictions on land use practices, and land governance and tenure (Verburg et al., 2013). Regardless, the land use harmonization process propagated uncharacterized spatial error unique to each IAM due to different sensitivities to the land regions delineated by each model.

The modeled land regions and corresponding initial state of these IAMs critically determine their land resource projections, and require a tremendous amount of data to ensure proper calibration to present day conditions. Model goals generally determine the type of land use model, and combined with available data, also the extent and resolution (Brown et al., 2013). IAMs have traditionally represented human activities in 10–30 geopolitical regions due to their origins as energy market models, and some of these models have recently disaggregated their geopolitical regions into smaller units for land use modeling, often using historical AEZs as the basis for this disaggregation (e.g., Schmitz et al., 2014). AEZs have been used in land use modeling for decades (e.g., Fischer and van Velthuizen, 1996; for review see FAO, 2016) to improve the real-world feasibility of modeled land use transitions by taking advantage of similarities in climate, soil, and topography (Lee et al., 2005). The use of AEZs to disaggregate geopolitical regions in IAMs also refines the spatial resolution of land use regions, and allows more detailed estimation of physical characteristics that are relevant for model outcomes (e.g., crop productivity, vegetation types, carbon contents). However, generating the IAM-relevant data associated with these AEZs is a major task.

A set of commonly used historical AEZs and associated land data were developed by the Global Trade Analysis Project (GTAP; Monfreda et al., 2009), and models that currently use this particular set of AEZs to disaggregate geopolitical regions include AIM (Hasegawa et al., 2015), FARM (Sands et al., 2014), GCAM (http://www.globalchange.umd.edu/archived-models/gcam/), and GTAP-AEZ (Hertel et al., 2009), among others. BLS-AEZ (Fischer et al., 2005) also uses similar terminology for classifying land, but with different criteria and sub-regional zone boundaries than the GTAP AEZs. However, the traditional IAM modeling paradigm does not include climate impacts, leaving an unexplored question regarding the representativeness of AEZ-averaged values in land use modeling under changing climate, in which case the AEZs may not retain their expected homogeneity. Note that the use of AEZs is not ubiquitous in land use modeling; other strategies to disaggregate geopolitical regions using primarily non-climatic criteria include grid cell boundaries (e.g., MAgPIE, Dietrich et al., 2014; GLOBIOM, Havlik et al., 2013), hydrologic watersheds (e.g., IMPACT, Rosegrant et al., 2012), and province/state boundaries (e.g., FASOMGHG, Beach et al., 2015). While these non-climatic boundaries avoid some issues associated with AEZs in the context of climate change, they can still suffer from lack of representativeness if they are not carefully defined, and they still generate model uncertainty associated with a particular delineation of the land surface.

Here we quantify the uncertainty in land resource projection due to spatial delineation of the land surface using the Global Change Assessment Model (GCAM), which is a community IAM that has been, and continues to be, used to generate scenarios for international climate assessments (van Vuuren et al., 2011a). While we use the AEZ methodology as implemented in GCAM, the present study is not an investigation of the effectiveness of current methods for representing agricultural climate impacts in land change models, nor is it an attempt to develop a new method of climate impacts assessment. Rather, we aim to 1) determine whether climatically defined boundaries, in particular AEZs, are appropriate in a land modeling context, and 2) characterize and quantify uncertainty in land resource projection due to spatial delineation of the land surface. To address these aims we generate new spatial boundaries (Section 3.1), evaluate the suitability of AEZ-based data sets for land use modeling under climate change (Section 3.2), quantify differences in inputs (Section 3.3) and outputs (Sections 3.4) due to different land use regions, and discuss the implications of these differences for land use modeling with and without climate impacts (Section 3.5).

2. Methods

GCAM is a community IAM that simultaneously represents human and biogeophysical processes associated with climate change (http://www.globalchange.umd.edu/archived-models/gcam/). The human system simulates activities within the global energy, industrial, and agricultural systems that are relevant for producing emissions and changing land use patterns. The biogeophysical system simulates feedbacks with the carbon cycle and the resulting impacts on the atmosphere and climate. A comprehensive data processing system generates GCAM input files from a wide variety of source data spanning resolutions from 5 arcmin grid cells to the globe.

To facilitate projection of both energy and land resources, GCAM contains two distinct modules—energy, and Agriculture and Land Use (AgLU)—that are linked via markets for bioenergy, nitrogen fertilizer, and (where applicable) greenhouse gas emissions. The AgLU component models land use decisions at scales that are smaller than the geopolitical regions at which markets for agricultural and energy goods are modeled. The intersection of 18 global AEZs with the geopolitical regions defines the land use regions in the AgLU module. The purpose of these smaller land use