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Global land-use allocation model linked to an integrated assessment model

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HIGHLIGHTS

- Development of a global land-use allocation model to be linked to integrated assessment models (IAMs).
- Description of the developed model and model evaluation for the estimated land-use allocation.
- Downscaling of the IAMs' regional land-use projections into a spatial land-use distribution.
- Illustration of influences of land-use downscaling on estimates of CO_2 emissions from land-use changes.

GRAPHICAL ABSTRACT

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ABSTRACT

We developed a global land-use allocation model that can be linked to integrated assessment models (IAMs) with a coarser spatial resolution. Using the model, we performed a downscaling of the IAMs' regional aggregated land-use projections to obtain a spatial land-use distribution, which could subsequently be used by Earth system models for global environmental assessments of ecosystem services, food security, and climate policies. Here we describe the land-use allocation model, discuss the verification of the downscaling technique, and explain the influences of the downscaling on estimates of land-use carbon emissions. A comparison of the emissions estimated with and without downscaling suggested that the land-use downscaling would help capture the spatial distribution of carbon stock density and regional heterogeneity of carbon emissions caused by cropland and pasture land expansion.

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1. Introduction

Land use and land-use changes involve interactions between human activities and natural systems. For example, deforestation, agriculture and bioenergy may affect ecosystems, water resources, biodiversity, and the climate system, whereas these biophysical systems may change human activities, decision making and the environment. Many stand-alone land-use models (LUMs) and land-use modules as a part of integrated assessment models (IAMs) have been developed with different modeling approaches, scales and resolutions, such as CAPS (Meiyappan et al., 2014), CLUEMondo (van Asselen and Verburg, 2013), GCAM (Wise and Calvin, 2011), GLOBIOM (Havlík et al., 2011), GLM (Hurtt et al., 2006), IMAGE (Letourneau et al., 2012), LandSHIFT (Schaldach et al., 2011), MAgPIE (Lotze-Campen et al., 2010), the Nexus land-use model (Souty et al., 2012), the Land-Use Trade-Offs (LUTO) model (Bryan et al., 2016) and so on. To understand uncertainty, difference in land cover projections were investigated in several approaches (Alexander et al., 2016; Gao et al., 2016). For instance, the difference in a wide range of model types and scenarios shows a higher degree of uncertainty in land-use projections than that in climate or earth system projections. This analysis raised as a future challenge better understanding the assumptions driving land use model results and to reveal the causes of uncertainty in more depth to help reduce model uncertainty and improve the land cover projections.

Recently, an integration of Earth system models (ESMs) and IAMs has been increasingly needed for addressing the issues that are driven by integrative biogeophysical, socioeconomic and human decision-making perspectives (Bond-Lamberty et al., 2014; Hibbard et al., 2010). The collaboration of the two communities is expected to play an important role and to help better understand the role of both natural and human systems and their interaction. The ESMs capture geophysical aspects such as climate, global carbon cycle, terrestrial vegetation, and ocean ecosystem whereas the IAMs have focused on socio-economic aspects such as energy, economic systems, and associated greenhouse gas emissions and considered land use as a fundamental factor to produce agricultural and forest products. However, in the integration, there is a gap between their regional classifications. The ESMs have a grid-based spatial resolution, whereas most of the IAMs have aggregated regional divisions. To promote the integration, there is a need for downscaling of the socioeconomic, emission and land-use scenarios projected by IAMs. Hibbard et al. (2010) and van Vuuren et al. (2010) raise transparency and consistency as criteria of downscaling methodologies and requires diagnostics using different downscaling methods against historical data. Some land use models have been evaluated at country or regional scale (e.g. Kok et al., 2001), but global-scale evaluation is still limited due to data issues (Meiyappan et al., 2014). The model evaluation method presented here could be provided as an example for a global-scale model evaluation. Moreover, global-scale evaluation is important for better understanding of the role of land dynamics in global changes. Although an evaluation of model performance over the historical period does not necessarily guarantee a good performance for future, a high agreement of historical patterns provides information about the uncertainty of future scenarios for the global environmental assessment.

In this study, we developed a land-use allocation model that works with an IAM: the Asian-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model. To determine the uncertainty of estimated land-use patterns, we performed verification for a downscaling methodologies by applying the model to a historical period (see Section 2.2 for more detail). Moreover, we conducted a downscaling of aggregated land-use scenarios estimated by AIM/CGE into the gridded level using the model, and investigated the influences of the downscaling on estimates of land-use emissions.

2. Materials and methods

2.1. Land-use allocation model

2.1.1. Mechanism of land-use allocation

Fig. 1 shows the overall framework of the methodology. Regional aggregated land demand projected by AIM/CGE (17 regions) was fed into the land-use allocation model and was downscaled into grid cells (0.5° × 0.5°). The cropland and afforestation area was allocated based on profit maximization where a land owner would decide land-use sharing to obtain the highest profit under a given biophysical land productivity (production per unit area). Since this process was conducted in each region and grid cell, land transactions across the regions were not allowed. The allocation was conducted in 5-year steps. There were seven crop types, with or without irrigation (Table 1). The crop types were aggregated as cropland for model verification according to the availability of historical cropland data. Land for wood production was excluded from this work. To convert quantities of harvested wood into areas of land, information regarding the historical map of harvested aboveground biomass, and the subsequent recovery following wood harvesting and land-use abandonment are needed. However, no global, gridded, or historical record of these data are available (Hurtt et al., 2011).

2.1.2. Formulation

The following formulas refer to a certain year and region. The upper bars represent exogenous parameters.

Total profit was maximized as follows:

$$\Phi = \sum_{l,g} Z_{l,g} \rightarrow \mathrm{Max}. \tag{1}$$

where g is a set of grid cells, l is a set of land-use categories, Φ is total profit (million US$), and $Z_{l,g}$ is the profit of land-use category l in grid cell g (million US$).

The profit was represented as profit (S) minus land conversion cost ($a_{l,g}$) as shown in Eq. (2). The second term accounts for the land conversion cost by multiplication with the increase in the fractional area of land-use from the previous year ($\Delta YP_{l,g}$). For this calculation, land-use patterns in the previous year were fed into the next year's calculation.

$$Z_{l,g} = \left(Y_{l,g} \cdot \overline{S_{l,g}} - \overline{a_{l,g}} \cdot \Delta YP_{l,g}\right) \cdot \overline{GA_g}, \qquad g \in G, l \in L \tag{2}$$

Subject to

$$Y_{l,g} - \overline{Ypre_{l,g}} = \Delta YP_{l,g} - \Delta YN_{l,g} \tag{3}$$

where $Y_{l,g}$ is the fractional area of each land-use category l in grid cell g (grid^{-1}), $S_{l,g}$ is profit per area (million US$/ha), $a_{l,g}$ is land conversion cost per area (million US$/ha), GA_g is grid cell area (ha/grid), $Ypre_{l,g}$ is the fractional area in the previous year (grid^{-1}), $\Delta YP_{l,g}(>0)$ is the increase in the fractional area from the previous year (grid^{-1}), and $\Delta YN_{l,g}(>0)$ is the decrease in the fractional area from the previous year (grid^{-1}).

The fractional area should not be negative:

$$Y_{l,g} \geq 0, \quad g \in G, l \in L \tag{4}$$

The total fractional area in a grid cell should be equal to or less than 1:

$$\sum_l Y_{l,g} \leq 1, \qquad g \in G, l \in L \tag{5}$$

For each land-use category, the total area of land allocated should meet the given land demand area LDM_l:

$$\sum_g \overline{GA_g} \cdot Y_{l,g} = \overline{LDM_l}, \qquad l \in L \cap l \neq havfrs \tag{6}$$