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A review of global potentially available cropland estimates and their consequences for model-based assessments

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Abstract

The world's population is growing and demand for food, feed, fiber, and fuel is increasing, placing greater demand on land and its resources for crop production. We review previously published estimates of global scale cropland availability, discuss the underlying assumptions that lead to differences between estimates, and illustrate the consequences of applying different estimates in model-based assessments of land-use change. The review estimates a range from 1552 to 5131 Mha, which includes 1550 Mha that is already cropland. Hence, the lowest estimates indicate that there is almost no room for cropland expansion, while the highest estimates indicate that cropland could potentially expand to over three times its current area. Differences can largely be attributed to institutional assumptions, i.e. which land covers/uses (e.g. forests or grasslands) are societally or governmentally allowed to convert to cropland, while there was little variation in biophysical assumptions. Estimates based on comparable assumptions showed a variation of up to 84%, which originated mainly from different underlying data sources. On the basis of this synthesis of the assumptions underlying these estimates, we constructed a high, a medium, and a low estimate of cropland availability that are representative of the range of estimates in the reviewed studies. We apply these estimates in a land-change model to illustrate the consequences on cropland expansion and intensification as well as deforestation. While uncertainty in cropland availability is hardly addressed in global land-use change assessments, the results indicate a large range of estimates with important consequences for model-based assessments.

Keywords: agricultural intensification, cropland expansion, land availability, land reserve, land use, land-change model

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Introduction

Human activity in the terrestrial biosphere is the single greatest factor modifying the structure of landscapes across the globe (Ellis & Ramankutty, 2008). Historically, the amount of land needed for collection and production of food, feed, fiber, and fuels to satisfy demand has experienced fluctuations as populations have grown or shrunk and methods of production have changed. As the human population has grown to over seven billion, affluence has increased, and demand for land-based resources has grown. The amount of land currently utilized to satisfy demand for these products has increased to occupy much of the most productive lands as well as many marginal areas. Some suggest that the area of land with productive potential is becoming scarce and this scarcity will shape future crop production (Lambin, 2012; Lambin *et al.*, 2013). Further population increase, coupled with an increase in affluence in a number of developing and emerging economies, will lead to a continued increase in demand for crop products. World population in 2050 is projected to be between 8.3 billion and 10.9 billion (United Nations, 2013). At the same time, the per capita food consumption is expected to increase from a global average of 2789 kcal per day in 1999–2001 to 3130 kcal per day in 2050 (Alexandratos, 2006). As a consequence, food production might need to increase by 100% or more relative to 2005 levels by 2050 to meet increased demand.

Global crop production is a function of the land area under cultivation and the intensity with which this land is cultivated. Consequently, changes in global crop production can originate from changes in the total area under cultivation and changes in the intensity with which this land is cultivated. Increases and decreases in the total area under cultivation are denoted as expansion and contraction respectively, where contraction can be due to land abandonment as well as conversion of cropland to other land uses, e.g. urbanization. Intensification and disintensification (sometimes called extensification; Feranec *et al.*, 2010) are the processes by which production per unit area can be altered through an increase or decrease in inputs, such as fertilizers, labor, technology, or outputs (Geist, 2006; Erb *et al.*, 2013). Whether production increases will be achieved through expansion of cropland or intensification of existing cropland depends to a large degree on the

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amount of land that is available and suitable for cultivation. Global estimates of potentially available cropland exist for different uses, such as food production and biofuel cultivation. These estimates differ substantially. Lambin *et al*. (2013) indicates that some of these estimates might overestimate the total available cropland considerably, or at least the amount of land that is available without further damaging the environment. However, potentially available cropland estimates have not been reviewed systematically. Consequently, the range of estimates and the assumptions causing the differences and uncertainties have not yet been identified.

Potentially available cropland estimates play a major role in many model-based assessments of future land-use change. Some models use potentially available cropland as a hard constraint to limit the maximum extent to which cropland can expand, such as the CLUMondo model (Van Asselen & Verburg, 2013). Other models use these estimates as a soft constraint, which influence land prices, which, in turn, can induce intensification instead of expansion, such as in the GLOBIOM model (Havlik, 2012). In both cases, different estimates can strongly influence model outcomes in terms of the area used, the locations of use and the intensity of use, which all have impacts on other ecosystems and ecosystem functioning. For example, Popp *et al*. (2012) demonstrate with the MAgPIE model that allowing cropland to expand into all Global Agro-Ecological Zones (GAEZ)-determined suitable land, including forests, results in a 160 million hectare expansion of cropland by 2095, while not allowing cropland expansion into forests results in only a 35 million hectare increase in cropland by the same time. However, while many land-change models apply cropland availability estimates as an input, most use only one single estimate. Consequences of assumptions and uncertainties in cropland availability in model-based assessments are not well understood.

In this study, we aim to provide a review of global cropland availability estimates, the causes of differences between estimates and uncertainties associated with the estimate, and illustrate the impact of different estimates on model-based land-change assessments. We collected and compared estimates for global cropland availability and reviewed how they were used in global land-change assessments. Subsequently, we compared the institutional and biophysical assumptions used to calculate these estimates to better understand the origin of the differences. We then synthesize these criteria and use them to produce a high, a medium, and a low potentially available cropland estimate, which are subsequently used to analyze the land-use consequences of different estimates in a spatially explicit land system change model.

Materials and methods

A review of potentially available cropland estimates and their application in land-change models

We explored existing literature for estimates of potentially available cropland and the assumptions underlying these estimates. Estimates were found by systematically searching in Google Scholar using 'land availability', 'agricultural expansion', 'potential agricultural land', 'land balance', and 'land reserve' as search terms. Estimates were included in this review if they report land availability for cropland or biofuels on a global scale, together with an explicit listing of the criteria used for identifying potentially available cropland. From the selected studies, we recorded the estimated area, and the assumptions underlying these estimates. These assumptions include land uses or covers that are allowed to convert into cropland, institutional constraints, and biophysical constraints. We recorded all assumptions as well as the datasets that were used to derive the potentially available cropland estimates.

To allow for a legitimate comparison, estimates were processed to derive the total potentially available cropland area, including those currently used as cropland. Hence, in the cases where only land available for cropland expansion was reported 1550 million hectares were added, as this was the average estimate of current globally cultivated area (Bruinsma, 2009; Lambin *et al*., 2013).

A survey was sent to land-change modelers with questions designed to understand the role of potentially available cropland in their models. Eleven models at global or continental scale were represented in the survey: CAPRI (Britz, 2013), CLUMondo (Van Asselen & Verburg, 2013), GCAM (Patel & Clarke, 2012), GLOBIOM (Havlik *et al*., 2011), GTAP-AEZ (Hertel *et al*., 2013), IMAGE (Bouwman *et al*., 2010), IMPACT (Rosegrant *et al*., 2012), LandSHIFT (Schaldach *et al*., 2011), MagPie (Lotze-Campen *et al*., 2008), MIRAGE (Decreux & Valin, 2007), and NEXUS (Souty *et al*., 2012). The surveys were preliminarily filled in based on information found on model websites and in literature explaining model function. They were then sent via email to the people listed as responsible for each model asking that the prefilled information be verified, corrected, or added to. The questions asked in the survey include:

- Is the quantity of land available for cropland expansion an input to the model, and if so how is it derived?
- Is the potentially available cropland estimate a binary or a gradient representing land suitability?
- How does the potentially available cropland estimate affect your model's results?

Land-use model sensitivity to cropland availability

The influence of variations in cropland availability estimates was illustrated by simulating future land system changes using different assumptions for cropland availability. Grouping the estimates from the reviewed studies based on their biophysical and land-use/cover constraints resulted in three groups of estimates representative of high, medium, and low cropland availability estimates. On the basis of the underlying assumptions, we reproduced three maps of potentially available cropland, corresponding to the three identified groups, and implemented these in the CLUMondo land system change model (Van Asselen & Verburg, 2013). We selected three world regions to assess the influence of different estimates: Southeast Asia, Central America, and Eastern Europe. These regions were selected because of the different quantities of increase in demand for crop production expected under the conditions of the OECD scenario (OECD, 2012), respectively exhibiting a 29%, 45%, and a 19% increase in production between the years 2000 and 2030. To allow comparison of impacts on land system choices and land allocation patterns, it was assumed that overall regional demand for crop production was not affected by differences in cropland availability, either through price mechanisms or by displacement of production. Although this assumption may not be realistic, it allows a more straightforward comparison of the model sensitivity toward different cropland availability estimates.

The data used to produce the three cropland availability estimates for the model experiment are outlined in Table 1. Land-cover data were derived from the Global Land Cover 2000 dataset (GLC2000). This land-cover dataset was chosen because it represents the land cover at year 2000, the same year as the start year of the CLUMondo land-change model in which the three estimates are applied. We reclassified the original 22 GLC2000 land-cover classes to match the 17 International Geosphere-Biosphere Programme (IGBP) land-cover classes according to the groupings described in Herold *et al.* (2008) because these classes best matched the land-cover classes described in the literature of cropland availability estimates. These IGBP land-cover classes were then used, in addition to biophysical and institutional constraints, to define areas to be excluded from the high, medium, and low estimates that were produced. We used the World Database on Protected Areas and areas designated as protected prior to or including the year 2000 were identified. From these protected areas, those designated with the International Union for Conservation of Nature (IUCN) codes V and VI were not regarded as a limit to cropland expansion as cropland can exist in these areas. Subsequently, a 15% reduction in area was applied to the three estimates to account for portions of cell areas that are not used for cropland. Studies have shown that cropland estimates based on raster cells often overestimate the true amount of cropland because they do not account for infrastructure, settlements, and other areas that are unsuitable for crops at the subpixel level (Young, 1999; Fritz *et al.*, 2013). Verburg *et al.* (2009), through an analysis of cropland across Europe, found that between 3% and 20% of the main (large-scale) cropland areas were occupied by infrastructure, buildings, or other nonproductive landscape features.

We used the CLUMondo model to demonstrate the sensitivity of a land-change model to the range of global cropland availability estimates. CLUMondo is a forward looking global model that simulates land system changes as a function of exogenously derived demand for crop production, livestock, and area for urban uses (Van Asselen & Verburg, 2013). A quality of the CLUMondo model is that intensification/disintensification and expansion/contraction (Table 2) of cropland area is accounted for endogenously. Based on induced intensification theory (Turner & Ali, 1996), the model simulates intensification of agricultural management upon a combination of increasing demands and decreasing land available for expansion of cropland area. As each productive land system considered in the model has an associated yield and cropland area, it is possible to analyze changes in cropland intensity and area over time as a function of various model parameters that are set according to scenario conditions. The application of the CLUMondo model in this study uses the model configuration presented in Van Asselen & Verburg (2013), based on the OECD scenario (OECD, 2012). To test alternative specifications of cropland availability, the application of the CLUMondo model was adjusted to reflect the assumptions on cropland availability consistent with the generated cropland availability maps. Land system conversions are constrained in the model by a conversion matrix which defines realistic and allowed conversions between land systems. This conversion matrix was adjusted to reflect the land uses that are allowed to convert into cropland in the different estimates. For example, in the high estimate, forest areas are available to convert into cropland, while this conversion is not allowed in the medium and low estimates. Consequently, the land system ‘dense forest’ is allowed to transition to cropland according to the conversion matrix using the high estimate, while in the simulations using the medium and low estimates this transition is not allowed.

The three modeled world regions face an increasing demand for cropland production over the simulation period, which can be met by a combination of cropland expansion and cropland intensification. As the model simulated land

Table 1 Data sources used to reproduce the high, medium, and low potentially available cropland estimates

Data	Data source	Citation
Land cover	Global Land Cover 2000	Fritz *et al*., 2003;
Protected areas	World Database on Protected Areas	IUCN, UNEP, 2009;
Aridity index	CGIAR-CSI Global-Aridity and Global-PET Database	Zomer *et al*., 2007, 2008;
Elevation	WorldClim 30 s resolution ESRI GRID of Altitude	Hijmans *et al*., 2005;
Soil conditions	FAO Digital Soil Map of the World	FAO, 2003;
Growing season length and temperatures	FAO Global Agro-Ecological Zones database	IIASA/FAO, 2012

Table 2 Definitions of the terms used to discuss intensity and area changes in cropland as defined in Geist (2006)

Term	Definition
Intensification	Increasing cropland inputs, labor, or capital, to improve crop yield
Disintensification	Decreasing cropland inputs, labor, or capital
Expansion	Increased cropland area due to conversion from of other land system types
Contraction	Decreased cropland area due to conversion of cropland to another land system type

system changes in an integrated manner contraction or disintensification of current cropland systems may take place due to increases in grassland in response to livestock demand or urbanization. Model results were assessed in terms of the share of production increase that was met by expansion of cropland area as compared to the share that could be attributed to the intensification of cropland areas, which was calculated as follows:

$$\text{Crop}_{\text{intens}} = \sum_i \Delta Y_i * A_{\text{end}_i}$$

$$\text{Crop}_{\text{area}} = \sum_i \Delta A_i * Y_{\text{start}_i}$$

where $\text{Crop}_{\text{intens}}$ is the total production change due to changes in the intensity of crop production, $\text{Crop}_{\text{area}}$ is the total production change due to changes in the cropland area, Y is the average yield (tons per km^2) in a cell, A is the total cropland area (km^2) in a cell, and i indicates the cells on the map. The shares of cropland area and cropland intensity of the respective land systems were derived from the global land systems map developed by Van Asselen & Verburg (2012). We further assessed the consequences of cropland changes in terms of forest cover changes.

Results

Estimates of potentially available cropland

The systematic search for potentially available cropland estimates yielded nine studies, which together contained 15 estimates; 12 estimate land available for biofuel production, and three calculate land area for all crops. Figure 1 provides an overview of these estimates, ranging from a low of 1552 mha to a high of 5131 mha. This includes land currently used for crop production and land that is potentially available for crop production if converted from its current state. The wide range of estimates of potentially available cropland covered by the different studies is mainly caused by differences in the land-use and land-cover classes they assumed to be available and whether or not protected areas are explicitly considered. On the basis of the land-use and land-cover classes that were included, we identified three groups of estimates. High estimates calculate cropland availability based on the land's ability to produce, mainly relying on biophysical

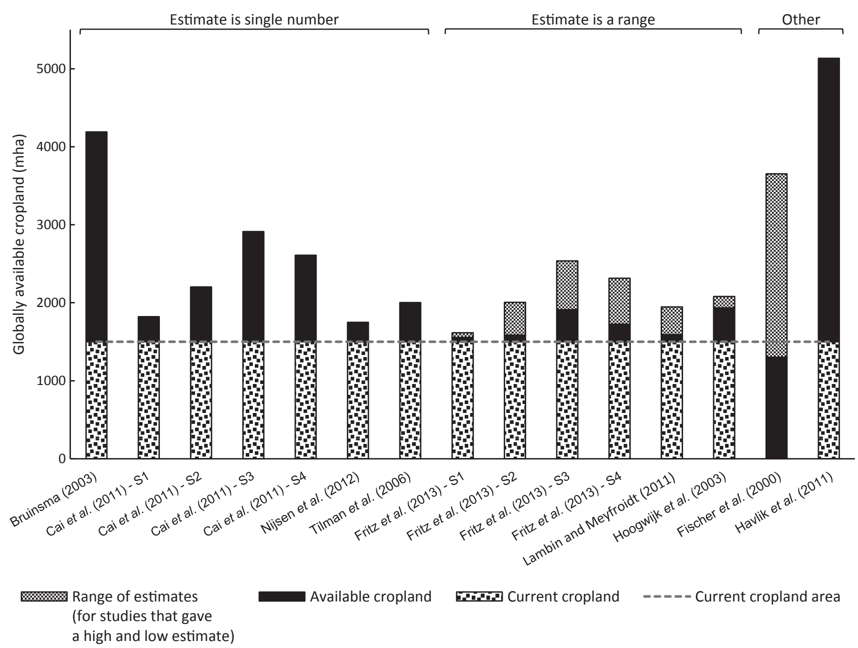

Fig. 1 Overview of reviewed estimates of potentially available cropland compared to the current amount of cropland.

constraints to production (Havlik *et al.*, 2011). Medium estimates allow cropland expansion into natural areas, but do not allow deforestation (Hoogwijk *et al.*, 2003). Low estimates allow expansion only in areas where natural vegetation is locally interspersed with cropland.

Estimates based on comparable assumptions about land-use and land-cover changes that are allowed still show a large variability in their estimates for potentially available cropland. High estimates exhibit a within-category difference of 40% relative to the lowest estimate in this category, medium estimates show a within-category difference of 84%, and low estimates show a 17% within-category difference. These differences can be attributed to the use of different underlying data sources and also in part to assumptions about biophysical constraints for cropland expansion. Nijsen *et al.* (2012) and Cai *et al.* (2011) use only land-use/cover to exclude areas from their available land estimates, while Havlik *et al.* (2011) and Bruinsma (2003) include additional biophysical constraints, such as slope and precipitation. Lambin & Meyfroidt (2011) explicitly consider protected areas, which are not included in any other estimate. Table 3 provides an overview of all constraints used in the reviewed estimates.

Cropland availability estimates in large-scale land-change models

Quantifying land that is available for cropland expansion is an essential step for assessing scenarios of future land change (Verburg *et al.*, 2006; Hertel, 2011). Potentially available cropland in land-use models is either based on existing estimates or computed based on similar assumptions. For example, the GCAM model (Patel & Clarke, 2012) excludes tundra, desert, and built-up areas, and the Nexus model (Souty *et al.*, 2012) excludes forested areas. Other models assume that cropland can expand only within areas covered by certain land-cover categories, such as arable land and grassland, as is the case in the CAPRI model (Britz, 2013). A third method for quantifying available cropland in models is through defining envelopes of biophysically suitable areas based on an analysis of the current conditions under which cropland is found, as in the original implementation of the CLUMondo model (Van Asselen & Verburg, 2013).

The amount of available cropland and its location influences land-change models in two ways. First, it influences the distribution of production increase over intensification and expansion of cropland to match increasing demand levels. Second, it determines where intensification and expansion take place. CAPRI (Britz, 2013), GLOBIOM (Havlik *et al.*, 2011), and MIRAGE (Decreux & Valin, 2007) determine the amount of land that will actually convert to agriculture through the use of a land supply curve. A land supply curve relates the area used for crop production to the cost of land or land conversion. The demand for products (i.e. the price of products) determines the land area used to maximize profitability. When more potential cropland is available, the cost of land (conversion) is lower; therefore cropland expansion is more favored. In contrast, when less potential cropland is available, the same conversion has a higher associated cost and cropland intensification may be favored (Prins *et al.*, 2011). In contrast to most economic models that account for cropland availability at a world-region level, CLUMondo considers cropland availability on a local scale using a neighborhood function (covering ca. 770 km^2). Cropland is thereby more likely to expand in areas with high cropland availability in the neighborhood, whereas locations with low cropland availability are more likely to intensify their production system (Van Asselen & Verburg, 2013).

High, medium, and low estimates of potentially available cropland

High, medium, and low estimates of global potentially available cropland were produced according to the land cover and biophysical condition exclusions applied in the various studies as shown in Table 4. After applying these constraints and assuming that on average 15% of a raster cell is occupied by nonproductive uses the totals of our high, medium, and low estimates are 5333 mha, 2926 mha, and 1867 mha respectively.

The values for our high, medium, and low estimates are within the range of high, medium, and low estimates found in our literature review. Figure 2 shows the global distribution of available cropland for the three estimates. Areas are characterized as either completely available or completely unavailable, without considering partial availability or gradients at the scale of a cell. The impact of assuming that forests are available for cropland expansion in the high estimate is visible particularly in the Amazon and the African Congo regions. Similarly, the effect of allowing open shrublands, savannas, and grasslands to be utilized for agriculture in the medium and high estimates is most visible in northern and eastern Australia. Protected areas were only included in the medium and low estimates, while the high estimate primarily shows what areas are suitable for cropland regardless of protected status. As there is little difference in the biophysical constraints applied across the estimates reported in the literature, the same biophysical constraints were

Table 3 Literature sources that provide estimates of potentially available cropland, their biophysical, land-use/cover constraints, estimate of available cropland, and the grouping in this study as high, medium, or low estimates of potentially available cropland

Source of estimate	Factors used to exclude areas	Estimate of land for	Estimated global potentially available cropland (mha)	Categorization
Havlik *et al*. (2011)	Elevation >3500 m; Population density >1000 people per km^2; Average growing season temperature <10 °C; Aridity index <0.65 All land covers except for forest, grassland, agriculture/cropland, and other natural vegetation	Biofuels	5131	High
Bruinsma (2003)	Slope >30%; Soils <50 cm deep; Soils with <18% clay; Soils with >65% sand; High salt content soils; Gypsisols; Salic and sodic phase soils; and Dunes, shifting sands, salt flats, glaciers, snow caps; Length of growing period (with average temperature <5 °C) <120 days	Agriculture	4188	High
Fischer *et al*. (2000)	Same as Bruinsma (2003)	Agriculture	3651	High
Cai *et al*. (2011) *Scenario 3*	All land covers except mixed cropland and grassland, cropland, shrubland, savanna, and grassland	Biofuels	2911	Medium
Cai *et al*. (2011) *Scenario 4*	All land covers except mixed cropland and grassland, cropland, shrubland, savanna, grassland, and pastureland	Biofuels	2607	Medium
Fritz *et al*. (2013) *Scenario 3*	All land covers except mixed cropland and grassland, cropland, shrubland, savanna, and grassland	Biofuels	1909 to 2535	Medium
Fritz *et al*. (2013) *Scenario 4*	All land covers except mixed cropland and grassland, cropland, shrubland, savanna, grassland, and pastureland	Biofuels	1723 to 2314	Medium
Cai *et al*. (2011) *Scenario 2*	All land covers except mixed cropland and grassland, and cropland	Biofuels	2202	Medium
Hoogwijk *et al*. (2003)	All land covers except cropland and grassland		1930 to 2080	Medium
Fritz *et al*. (2013) *Scenario 2*	All land covers except mixed cropland and grassland, and cropland	Biofuels	1584 to 2005	Medium
Tilman *et al*. (2006)	All land covers except cropland and grassland	Biofuels	2000	Medium
Lambin & Meyfroidt (2011)	Population density >25 people per km^2 Forested, protected, and built-up	Agriculture	1589 to 1945	Medium
Cai *et al*. (2011) *Scenario 1*	All land covers except for marginal mixed cropland and natural vegetation	Biofuels	1820	Low
Nijsen *et al*. (2012)	All land covers except for cropland and pastures	Biofuels	1747	Low
Fritz *et al*. (2013) *Scenario 1*	All land covers except for marginal mixed cropland and natural vegetation	Biofuels	1552 to 1613	Low

applied to all estimates. This means that the differences in the estimates come from the assumptions on availability/protection of different land-cover types only. The spatial data for these cropland availability estimates are made available at http://www.ivm.vu.nl/landavailability.

Scenarios for intensification or expansion

In the model simulations, increased demand for production can be fulfilled by intensifying existing cropland systems, or by converting other land systems into cropland systems. Figure 3 shows the relative contribution to production increases that intensification, disintensification, expansion, and contraction have for each region during the simulation period. Southeast Asia had a 29% increase in demand for crop production (212 million tons in 2000 to 299 million tons in 2030), Central America had a 45% increase (12 million tons in 2000 to 22 million tons in 2030), and Eastern Europe had a 19% increase (115 million tons in 2000 to 143 million tons in 2030). In all regions, it is clear that lower cropland availability leads to a higher percentage of the increased production being attributed to intensified

Table 4 Land-cover, institutional, and biophysical constraints for the high, medium, and low potentially available cropland estimates reproduced for this study. For the land-cover and institutional constraints, an 'X' denotes exclusion from that estimate, '•' denotes not excluded

	Exclusion factor		
Constraint	High estimate	Medium estimate	Low estimate
IGBP land-cover classes (full class names in parentheses when not already specified)			
Croplands and cropland/natural vegetation mosaics	•	•	•
Open shrublands, savannas, and grasslands	•	•	X
Closed shrublands and woody savannas	•	X	X
Forests (Evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forests)	•	X	X
Barren or sparsely vegetated	•	X	X
Snow and ice	X	X	X
Urban and built-up	X	X	X
Permanent wetlands	X	X	X
Water bodies	X	X	X
Institutional			
Protected areas	•	X	X
Biophysical			
Aridity index	<0.2	<0.2	<0.2
Elevation	>3500 m	>3500 m	>3500 m
Slope	>30%	>30%	>30%
Soil clay content	<18%	<18%	<18%
Soil sand content	>65%	>65%	>65%
Soil salt content	High	High	High
Gypsiol soils, salic and sodic phase soils, dunes, shifting sands, salt flats, glaciers	Excluded	Excluded	Excluded
Length of growing period (with average temperature <5 °C)	<120 days	<120 days	<120 days
Average growing season temperature	<10 °C	<10 °C	<10 °C

land-use systems, and a lower percentage attributed to cropland expansion. Southeast Asia and Eastern Europe respond to lower potentially available cropland by increasing their production with greater intensification. In Central America, however, there is less production gain from intensification with low cropland availability than with medium cropland availability, but this is more than compensated for by a smaller production loss from disintensification. Disintensification is often the result of a conversion into less intensively managed land systems in more marginal areas. When accounting for both intensification and disintensification the result for Central America still shows that lower cropland availability leads to higher land-use intensity. In the high availability estimate, 28% of increased production is due to net intensification (gross intensification and

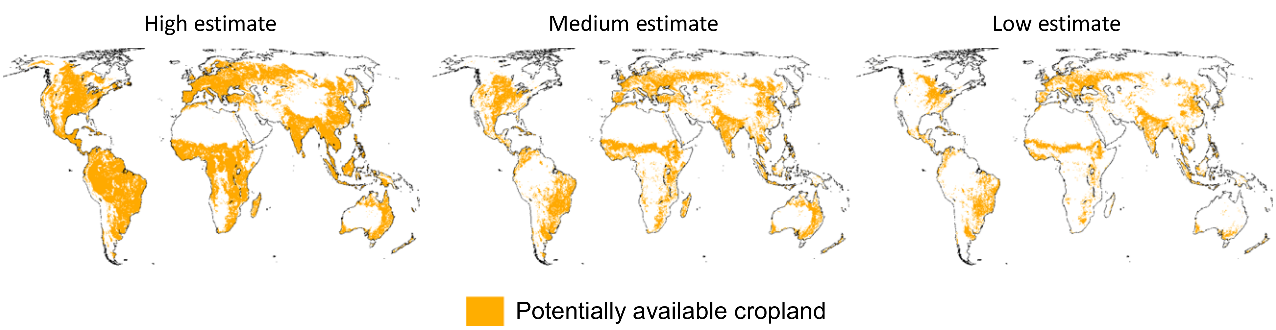

Fig. 2 Global potentially available cropland according to the high, medium, and low reproductions based on the literature review.

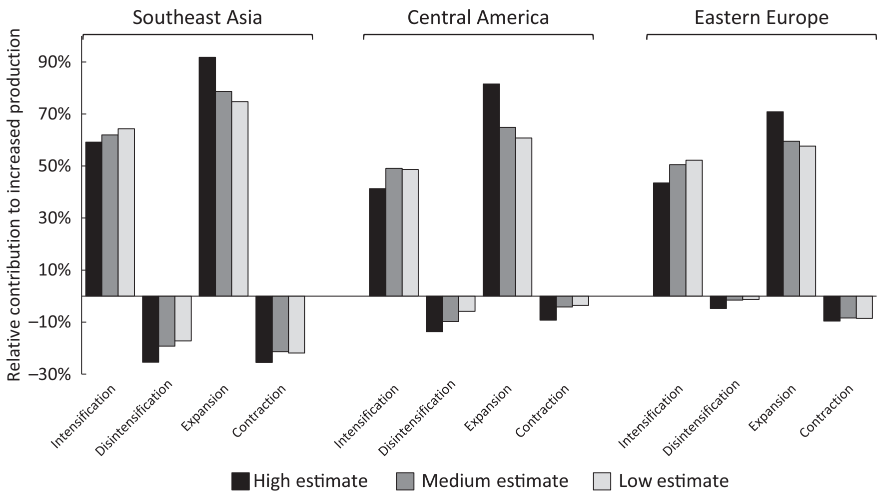

Fig. 3 Relative contribution of intensity and area changes to fulfill increased demand for crops under three cropland availability scenarios from 2000 to 2030. All three regions show that a decreasing amount of cropland availability leads to less expansion, which is compensated by intensity changes. A more detailed explanation of this figure is provided in the text.

gross disintensification combined), while with the medium estimate it is 39%, and with the low estimate it is 43%. The same trend is observed in Southeast Asia, with 34% of production increase realized by net intensification using the high, 43% using the medium, and 47% using the low estimate, and Eastern Europe, with 39% of increased production being due to changes in intensity in the high, 49% in the medium, and 51% in the low estimate. The different spatial arrangements of land systems due to cropland availability for Southeast Asia can be seen in Fig. 4. Also, Fig. 5 shows that all three regions exhibit a trend of decreased forest loss as less land is considered available for cropland expansion, with the largest decrease in forest loss in the high to the medium estimate. This is a direct consequence of forests being available for agriculture in the high estimate of cropland availability, while they are not available in the medium estimate. A smaller decrease in forest loss is seen from the medium to the low cropland availability estimate. Model assumptions on the availability of forest land thus directly influence the change in forest cover simulated by land-change models.

Discussion

Review of potentially available cropland estimates

The review of global cropland availability estimates shows that these estimates vary widely, both in quantity, and in the assumptions applied in their calculations, resulting in them ranging from 1.5 billion hectares to 5.1 billion hectares. The smallest estimates indicate that there is no room for cropland expansion, while the highest estimates indicate that cropland could potentially expand to over three times its current area. The differences in these estimates can be attributed to assumptions on cropland availability and the data used in their calculations.

The differences in the reviewed estimates are mainly due to assumptions regarding the availability of specific land covers or uses for conversion into cropland, which are often subject to institutional restrictions. To a large extent, the differences in cropland availability estimates reflect the underlying purpose or meaning of the estimates. Some estimates reflect all land that could technically be used for crop production, while others estimate the amount of land that can be used for cropland with relatively low ecological and social costs. The former typically identifies forests and protected areas as available for cropland, while the latter typically excludes forested areas. Bruinsma (2003) and Fischer *et al*. (2000) employ the GAEZ methodology, which does not account for the current use or institutional status of the land, but rather focuses strictly on the biophysical characteristics such as slope and soil content, while all other studies strictly exclude areas where their current status makes it prohibitively challenging to convert to agriculture, such as urban areas.

Historically, cropland expansion has played a large role in global deforestation (Gibbs *et al*., 2010) and while efforts to curb this have been implemented, in many areas clearing forest for cropland expansion still occurs (Meyfroidt & Lambin, 2011). Hence, low estimates of cropland availability would

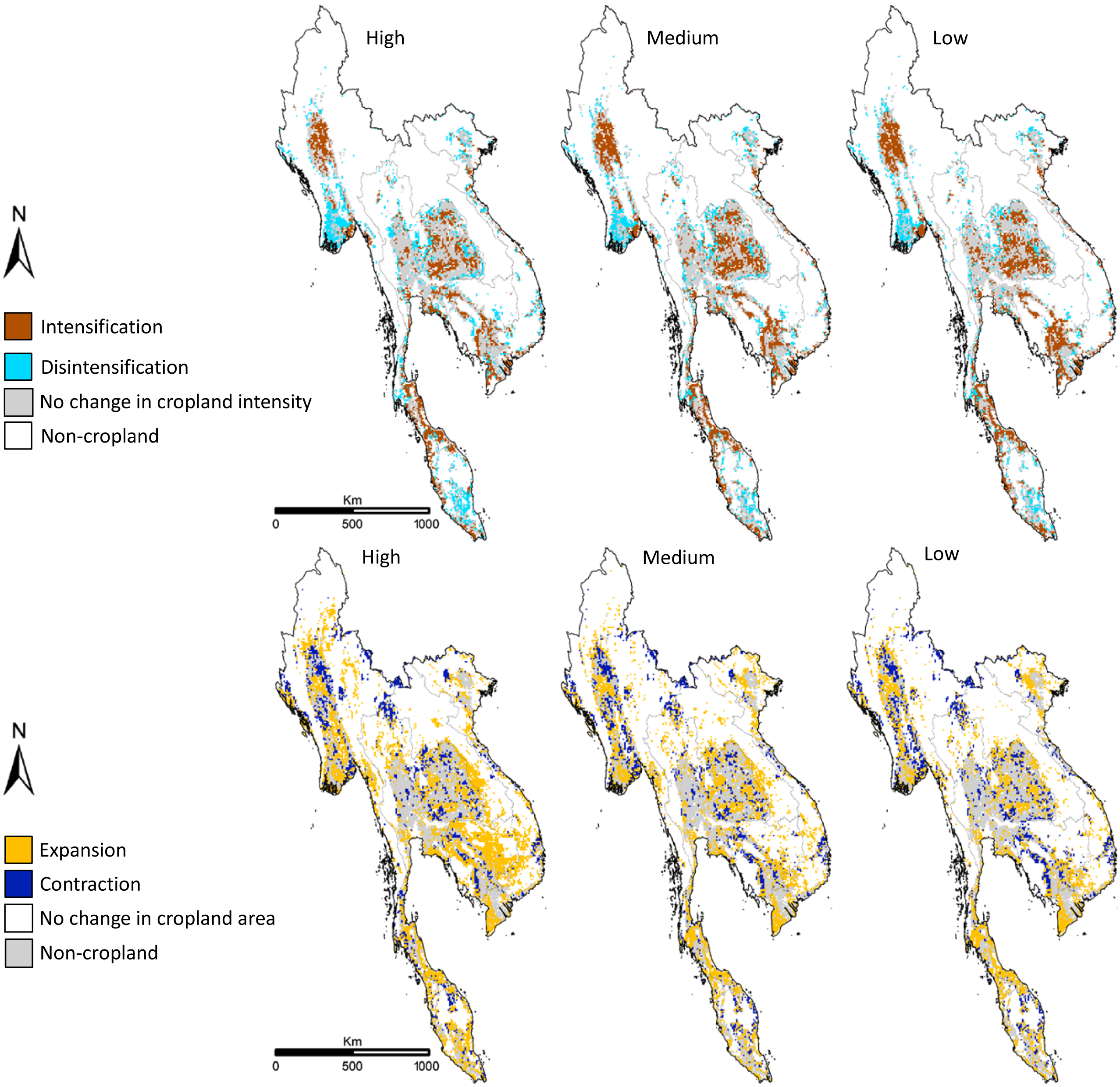

Fig. 4 The effects of the high, medium, and low cropland availability estimates on cropland intensity and area cultivated when applied in the CLUMondo land-change model in Southeast Asia. The top three maps show intensification and disintensification on cropland and mosaic cropland between year 0 and year 30. The bottom three maps show expansion and contraction of cropland area between year 0 and year 30.

require a deviation from the practice of deforestation for crop production. Consequently, this difference can be considered institutional, because policies and regulating bodies can induce or restrict conversion of one land cover or use to another (Phalan *et al.*, 2011). Other institutional constraints, represented as protected areas, are only considered explicitly in one of the reviewed estimates (Lambin & Meyfroidt, 2011). However, Lambin *et al.* (2013) argue that social tradeoffs, such as hunting grounds and recreation areas, and ecological tradeoffs, such as ecosystem services like water filtration, actually make some areas prohibitively costly to convert to cropland, and therefore their lack of inclusion in cropland availability estimates leads to an overestimation.

Biophysical assumptions can influence the cropland availability estimates also. Havlik *et al.* (2011) apply biophysical thresholds for temperature, soil

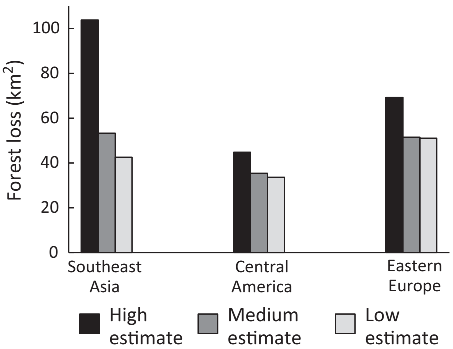

Fig. 5 Simulated loss of forested area in Southeast Asia, Central America, and Eastern Europe between year 2000 and year 2030, for each of the high, medium, and low cropland availability estimates.

characteristics, and others, while (Cai *et al.*, 2011) do not explicitly define any biophysical characteristics of their estimates. However, these biophysical constraints are not a major source of differences in the estimates, as biophysical properties are already reflected in the land covers or uses available for conversion. For example, arid areas are typically not covered with cropland, grassland, or forest land, and therefore they would be excluded based on their current land cover already. For this reason, biophysical constraints were applied uniformly across the three estimates reproduced for this study. Hence, they are not responsible for differences in the estimated quantities of available cropland or differences in the modeled scenarios.

Different datasets are the main source of the discrepancies between estimates based on comparable assumptions. They resulted in differences of 40%, 84%, and 17% in within our high, medium, and low estimate groupings. As an illustrative example, when comparing the area of forest in the GLC2000 and GlobCover datasets, the difference is 153 million hectares (Fritz *et al.*, 2011). Also, utilizing the same data, but with a different analysis technique can yield different estimates: Fischer *et al.* (2000) and Bruinsma (2003) use the same underlying data, however their cropland availability estimates differ by 537 mha because Fischer *et al.* (2000) do not include marginally suitable land in their global totals while Bruinsma (2003) does.

Many of the estimates were developed for biofuel crop production, identifying the amount of land where biofuels could be produced without impacting food production. However, as biofuel crops and food crops can be grown in very similar, if not identical, conditions we treated these estimates as equal. There are, however, a number of biofuel crops that are also suitable for more marginal areas where most food crops cannot provide profitable yields in commercial crop production. The potentials of using marginal land for biofuels are debated in the literature (Rathmann *et al.*, 2010) and in most cases biofuel production would face the same profitability constraints as arable use in these areas, while subsistence farming would otherwise be possible in those areas. We do not expect that the difference between land available only for biofuel cultivation and

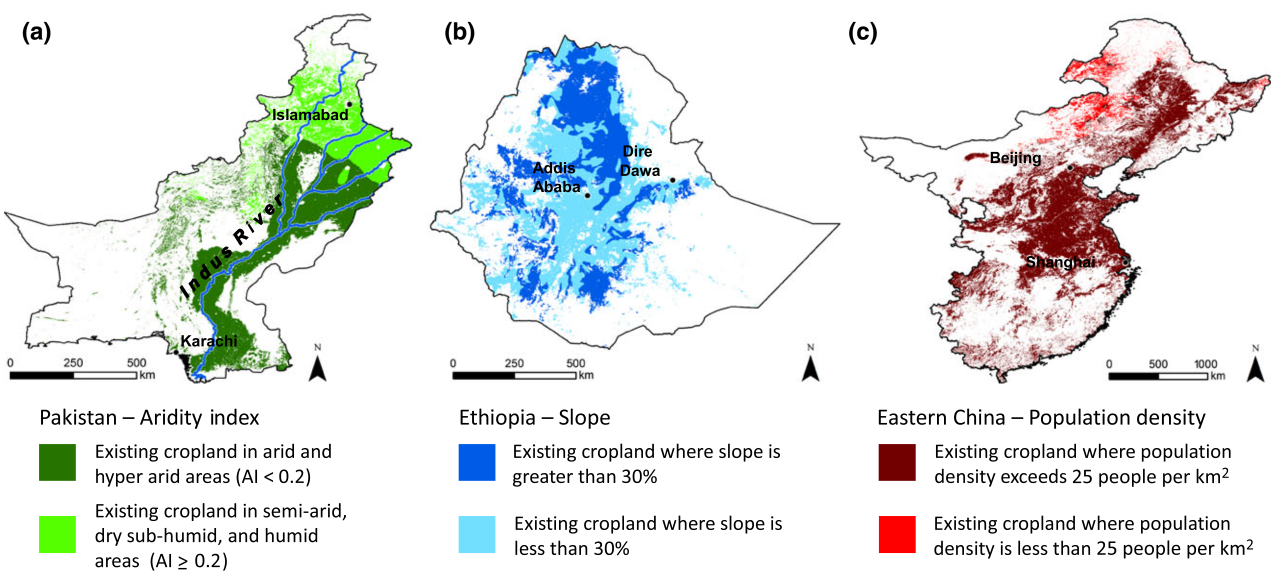

Fig. 6 Examples of areas where biophysical constraints indicate that areas where agriculture currently exists are in fact unsuitable for agricultural production. (a) In Pakistan, 68% of existing cropland is located in areas with an aridity Index of less than 0.2, falling into the arid and hyperarid categorizations identified to have significantly lower productive capacity (Van Asselen & Verburg, 2012). (b) In Ethiopia, 46% of existing cropland is located on slopes with greater than a 30% grade. (c) In Eastern China, 88% of existing cropland is located in areas with population densities greater than 25 people per km^2.

that available for all crops explains the wide range of estimates. Moreover, in most land-use models no distinction is made between the cropland availability for either food or biofuel production. These estimates are generalizations of land that can be utilized for all crop types and do not convey the limitations for specific crops that require a much more strict set of biophysical characteristics.

Uncertainties

Data resolution and the scale of analysis are a major source of uncertainty in global scale cropland availability estimates. Fritz *et al.* (2013) make the point that local scale heterogeneity is not always captured in global datasets. Likewise, local scale practices are not always accounted for when applying constraints and thresholds at a global level. A more detailed analysis for some regions suggests that agriculture is currently practiced at several locations classified as 'not available' in most estimates. Figure 6 highlights three constraints that are used in the reviewed studies, but that are not necessarily a limitation. When an aridity index is used to distinguish hyperarid and arid areas (aridity index <0.2) as being unavailable for cropping (Zomer *et al.*, 2007, 2008), it eliminates roughly 68% of the current cropland area in Pakistan, primarily along the Indus River valley. Irrigation from the Indus River makes it possible to cultivate this area despite very low precipitation. Similarly, eliminating areas with a slope of greater than 30% from availability (Bruinsma, 2003) removes around 46% percent of the current cropland in Ethiopia, where it is common to cultivate terraced hillsides. Also, when areas with a population density greater than 25 people per km^2 are eliminated in eastern China (Lambin & Meyfroidt, 2011), around 88% of current cropland areas are eliminated. These are examples that highlight the challenges of attempting to apply global scale data and analyses to more local scale realities.

In addition to the macroscale uncertainties discussed above, there are also microscale contributors to uncertainty in estimates of global cropland availability. These are caused by subpixel heterogeneity, which is not captured by the classification or categorization of a pixel. Figure 7a and b show where subpixel heterogeneity can lead to an underestimation of available cropland. Figure 7a shows that this area is perceived by the data as having slopes too steep to grow crops (i.e. slope >30%) but when the individual pixel is analyzed, it is clear that there is an abundance of cropland on what appears to be relatively level ground. Figure 7b clearly shows cropland adjacent to poor and rocky soils, which is the reason for this pixel to be categorized as

Fig. 7 Examples of under- and overestimation of available cropland at the pixel level. The solid white outline is a cell from CLUMondo with an area of 85.56 km^2, while the diagonal white hatching demarcates subpixel areas where availability for cropland does not correspond with the estimate for the whole pixel. (a) This cell, in Thailand, is unavailable in all estimates due to its slope exceeding 30%, however there is clearly crop production here. (b) This cell, in Tajikistan, is unavailable in all estimates due to rocky debris and poor soils being categorized as unavailable, while ca. 40% of the cell is currently agriculture. (c) This cell, in the United States, is available in all estimates, however urbanization reduces the proportion of the available area in this cell. (d) This cell, in Canada, is available in all estimates, but the abundance of lakes here reduces the portion of the cell where crop production can take place.

unavailable. Figure 7c and d show where subpixel heterogeneity can lead to an overestimation of available cropland, as these pixels are available in the estimates that were produced for this study. Figure 7c shows that an urban area in the center of cropland takes up about 40% of the area, while Fig. 7d shows lakes present in a large portion of the cell. Like the macroscale snapshots discussed above, these microscale snapshots show that the fine scale processes taking place on the ground are not always captured by global scale analyses. These also show that at the raster cell level, it is uncommon that 100% of the cell can be cultivated. As subpixel information can lead to both under- and overestimation of results, it is not clear what the effect is on the overall estimation of global potentially available cropland.

Consequences for model-based land-change assessments

The high, medium, and low estimates of cropland availability reproduced in this study were applied in the CLUMondo model to assess the effects of the assumptions of availability. While the scale at which potentially available cropland influences land-use changes might be different in other land-change models, the type of response is similar. The three selected regions, Southeast Asia, Central America, and Eastern Europe, are quite different in terms of their current land systems, intensity of production, cropland available for expansion, and driving factors of change. However, they show very similar responses to differences in cropland availability. As land becomes scarcer, greater demand for crop production will be satisfied by increased production from intensive systems and less production from expanding systems. This behavior is, of course, a direct consequence of the conceptualization of land-change processes in the model which follows the generally accepted 'induced intensification' theory (Turner *et al.*, 1977). The partitioning and spatial impacts are, however, an emergent property of the model simulations and region-specific circumstances. Consequences of differences in cropland intensification or expansion are visible in the forest systems. There is a clear trend toward decreased forest loss with lower cropland availability. This can be explained by the lower estimates of available cropland, constraining on where agriculture can expand. Lower cropland availability causes intensification of existing cropland systems lowering the total cropland area required to meet the demand for crop production, thus leaving more space for natural areas including forests.

The demand for crop production was not influenced by the amount of available cropland in this study. This might cause an overestimation of the land sparing effects of intensification. Land-use intensification in a globalized world can cause land-use displacement: a shift of land use from one location to another (Lambin & Meyfroidt, 2011; Weinzettel *et al.*, 2013). Due to intensification, more land remains available for cropping and production will become cheaper, causing a shift in demand from other regions (Kastner *et al.*, 2014). In addition, on a global scale, Rudel *et al.* (2009) have shown that land-use intensification generates an increase in demand which partly counteracts the potential land sparing effects. As this effect was observed in almost all world regions, it is not the consequence of land displacements, but instead caused by an overall increase in demand. As Byerlee *et al.* (2014) suggest, though, technology-driven intensification results in greater land sparing than market-driven intensification. However, while land displacements and demand increases are likely consequences of intensification and related land sparing, it will not change the main patterns observed in our model result. Explicit analysis of the influence of potentially available cropland in global assessments will provide more insight in the tradeoffs between food production and conservation of important ecosystems.

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