A global analysis of land take in cropland areas and production displacement from urbanization

van Vliet, J.; Eitelberg, D.A.; Verburg, P.H.

published in
Global Environmental Change
2017

DOI (link to publisher)
10.1016/j.gloenvcha.2017.02.001

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
van Vliet, J., Eitelberg, D. A., & Verburg, P. H. (2017). A global analysis of land take in cropland areas and production displacement from urbanization. *Global Environmental Change*, *43*, 107-115. https://doi.org/10.1016/j.gloenvcha.2017.02.001

Global Environmental Change 43 (2017) 107–115

Contents lists available at ScienceDirect

Global Environmental Change

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

A global analysis of land take in cropland areas and production displacement from urbanization

Jasper van Vliet*, David A. Eitelberg, Peter H. Verburg

Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 14 January 2017
Accepted 1 February 2017
Available online 20 February 2017

Keywords:
Urban growth
Land-use change
Land-use intensity
Cropland expansion
Food security

ABSTRACT

Urban growth has received little attention in large-scale land change assessments, because the area of built-up land is relatively small on a global scale. However, this area is increasing rapidly, due to population growth, rural-to-urban migration, and wealth increases in many parts of the world. Moreover, the impacts of urban growth on other land uses further amplified by associated land uses, such as recreation and urban green. In this study we analyze urban land take in cropland areas for the years 2000 and 2040, using a land systems approach. As of the year 2000, 213 Mha can be classified as urban land, which is 2.06% of the earth's surface. However, this urban land is more than proportionally located on land that is suitable and available for crop production. In the year 2040, these figures increase to 621 Mha, or 4.72% of all the earth's surface. The increase in urban land between 2000 and 2040 is also more than proportionally located on land that is suitable and available for crop production, thus further limiting our food production capacity. The share of urban land take in cropland areas is highest in Europe, the Middle-East and Northern Africa, and China, while it is relatively low in Oceania and Sub-Saharan Africa. Between 2000 and 2040, urban growth caused the displacement of almost 65 Mton of crop production, which could yield an expansion of up to 35 Mha of new cropland. Land-use planning can influence both the location and the form of urbanization, and thus appears as an important measure to minimize further losses in crop production.

1. Introduction

Urbanization is taking place at unprecedented rates, due to global population growth and ongoing rural-to-urban migration (Angel et al., 2011; Jiang and O'Neill, 2015). For example, Lambin and Meyfroidt (2011), expect that between 2000 and 2030 land taken by urbanization will be of the same order of magnitude as the area required for cropland expansion, pastures, or biofuels in the same period. Similarly, Seto et al. (2011) project that the urban area will more than double in the majority of their global scenarios. The growing amount of land that is taken by urbanization also increases the competition with other land uses. This competition is particularly well documented for China, where unprecedented urban growth is threatening food security as increasing amount of cropland is converted (Jiang et al., 2013; Liu et al., 2005). As a consequence, a number of targeted policies have been implemented to prevent a further decline in cropland area and assure a minimum level of food security (Lichtenberg and Ding, 2008; Lu et al., 2015). However, cropland losses due to urbanization have been reported in other regions as well, including India (Pandey and Seto, 2015), Puerto Rico (del Mar López et al., 2001), Africa (Nkeki, 2016), and selected cities globally (Bagan and Yamagata, 2014).

Because built-up area covers only a small fraction of the earth, few global assessments include urban land (Alexander et al., 2017). A recent overview by Prestele et al. (2016) shows that five out of eleven global-scale land change projections represent built-up area, while the other six include only natural and agricultural land. However, the impact of urbanization on food production might be underestimated for several reasons. First, many urban areas are allocated in fertile (delta) areas, which means that food production and urbanization are in direct competition for land (Bren d'Amour et al., 2016; Thebo et al., 2014). Because urban growth typically takes place at the edge of existing urban areas (van Vliet et al., 2013), this competition is likely to continue in the near future. Second, urban growth is often assessed using built-up area, while a much larger amount of land is lost for crop production upon urbanization. This includes non-productive uses, such as golf courses, gardens, and sports areas, which are particularly found in more prosperous countries (Plieninger et al., 2015; Zasada et al., 2013). Third, urban growth is not only manifested by an expansion

* Corresponding author.
E-mail address: jasper.van.vliet@vu.nl (J. van Vliet).

http://dx.doi.org/10.1016/j.gloenvcha.2017.02.001
0959-3780/

of metropolises and other conurbations, but increasingly also as peri-urbanization and villages, which can take more land area per person. These processes are not frequently represented in large scale land assessments, as built-up area is rarely the predominant land cover at the level of a pixel (Verburg et al., 2013). Moreover, the impacts of urban land extend beyond the reduction of food production only, as it has been associated with fragmentation and habitat loss (McKinney, 2008), temperature increases by means of urban heat islands (Buyantuyev and Wu, 2010), changes in the provisioning of ecosystem services (Schneider et al., 2012), and alterations of the hydrological cycle (Shuster et al., 2005).

In this paper, we assess the amount of urban land take in the year 2000 and in the year 2040, using a projection from the CLUMondo land systems change model (van Asselen and Verburg, 2013). Land systems denote typical combinations of land covers and land usages, and thus allow to go beyond built-up areas strictly by assessing the influence of urban land systems as well as peri-urban and village systems. These impacts are compared against global estimates of land that is suitable for crop production as well as land that is available for crop production. Furthermore, we calculate the displacement of crop production between 2000 and 2040 as a consequence of urbanization, in order to quantify its contribution in global cropland expansion.

2. Methods

2.1. Mapping global land systems for 2000 and 2040

The analysis of urban land take is based on land systems maps for the years 2000 and 2040 (see Figs. S1 and S2). The use of land systems instead of land cover allows the depiction of typical combinations of land cover and land use intensity that exist in the landscape, while respecting the sub-pixel information (van Asselen and Verburg, 2012). The land systems approach is similar to the frequently used Anthromes (Ellis and Ramankutty, 2008), but, in contrast to Anthromes, land systems are mainly defined by their agricultural use.

The land system map for the year 2000 was created using a hierarchical classification tree as described in Eitelberg et al. (2016). This classification uses the pixel shares of forest, built-up, grassland, and cropland (Hansen et al., 2010; Ramankutty et al., 2008; Schneider et al., 2009), in combination with ruminant livestock density (FAO, 2007), and land management intensity (Neumann et al., 2010). Each of the 24 different classes is characterized by the average land cover composition, ruminant livestock density and crop production of all pixels with that particular land system within the same model region. Crop production is based on the regional specific mix of crops in the data provided in Monfreda et al. (2008), and specific crop types are not further assigned to specific locations. The land system map for the year 2000 is created at a spatial resolution of 5′, in the WGS 1984 Eckert IV equal area projection. All other spatial data in this study are converted into this projection and resolution. Two land systems are classified based on their share of built-up area: *urban* systems and *peri-urban and village* systems. Urban systems are defined by more than 25% built-up area, while peri-urban and village systems have more than 5% but less than 25% built-up land. We will hereafter refer to the combination of these two as ‘urban land’, and use ‘urban system’ only when referring to this particular land system. All other land systems can also contain small amounts of built-up land, but never more than 5% of the pixel area, and typically much less. At the same time, while the amount of built-up area is their defining characteristic, urban systems and peri-urban and village systems also contain other land cover types, produce crops, and contain livestock.

The land systems map for 2040 was generated using the CLUMondo land system change model (van Asselen and Verburg, 2013). In CLUMondo, changes are driven by an exogenous demand for goods and services, and allocated in yearly steps according to the local suitability, land system specific rules (including the neighborhood effect, conversion resistance, constraints for crop production, and land system specific conversions possibilities), and the competition between land systems based on the goods and services they provide. Local suitability is determined by empirical relationships between a given land system and a set of explanatory biophysical and socioeconomic variables, derived from a logistic regression analysis. We use the results of the baseline scenario presented in Eitelberg et al. (2016), which starts from the land system map for the year 2000, as described above. This scenario is based on the United Nations Food and Agriculture Organization’s

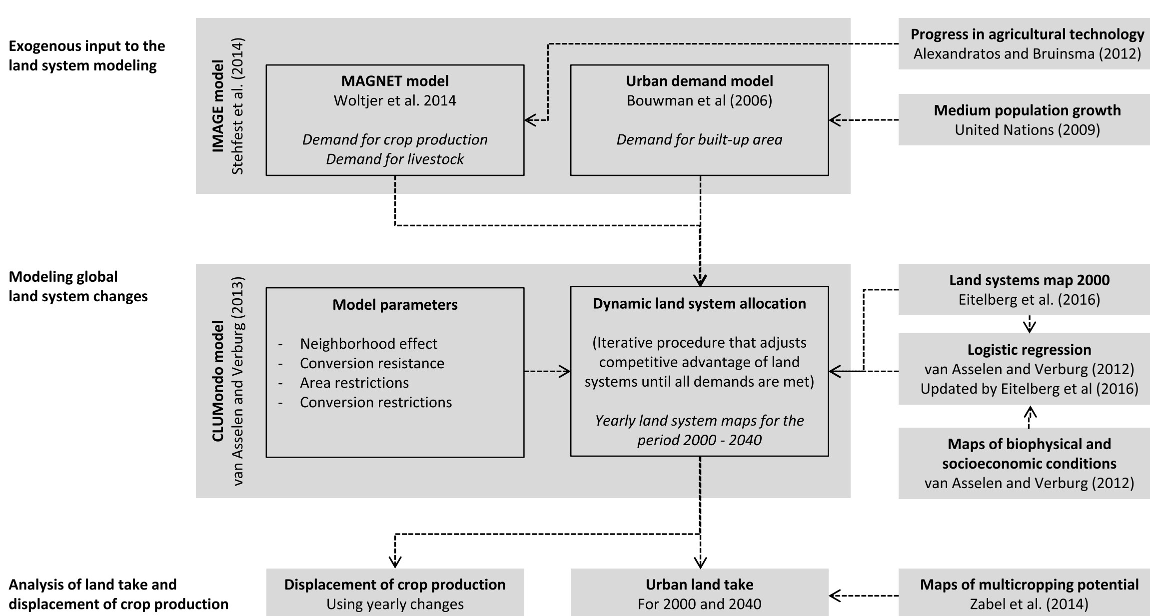

Fig. 1. Schematic representation of the study design, with the modeling and analysis in the center and data that is used as input on the right-hand side. Intermediate results that used in this study are indicated in Italics.

report titled *World Agriculture Towards 2030/2050, the 2012 revision* (Alexandratos and Bruinsma, 2012). The FAO scenario was implemented in the integrated assessment model IMAGE (Stehfest et al., 2014), which then provided projected demands for ten-year intervals for tons of crop production, and head of ruminant livestock, for 24 model regions. Within IMAGE, the MAGNET model accounts for agricultural trade by matching regional supply and demand for agricultural commodities (Woltjer et al., 2014). The demand for built-up area is based on the United Nations World population prospects, medium scenario (United Nations, 2009), which projects an increase from 6.1×10^9 people in the year 2000 to 8.8×10^9 people in the year 2040, globally. This projection was subsequently converted into a demand for built-up area by the IMAGE urban demand model (Bouwman et al., 2006). The yearly increase (in percentages) was subsequently included in CLUMondo to drive urban growth until 2040. Fig. 1 provides a schematic overview of the complete modeling chain.

The accuracy of the logistic regression analysis was assessed by means of the Receiver Operating Characteristic (ROC) value, which ranges from 0.5 (no signal) to 1 (perfect signal) (Swets, 1988). The ROC-value for the allocation of peri-urban and village systems, and urban systems was 0.90 and 0.97, respectively, while the ROC values for cropland systems ranged from 0.81 to 0.95, globally (van Asselen and Verburg, 2012). An overview of all biophysical and socioeconomic variables used in the logistic regression analysis is provided in van Asselen and Verburg (2013). A comparison shows that the hotspots for urbanization in our model results correspond largely with the hotspots for urbanization as identified in other studies. Similar to the world urbanization prospects (United Nations, 2014) our projection shows high urban growth rates in South Asia and China, and to a lesser extent in Africa. Similar hotspots are also identified by Seto et al. (2012a), who also points at Turkey and the Guinean forests in Western Africa. Our model also simulates a high urban growth rates in Turkey, while the urban expansion in Western Africa is spread over multiple countries (see Figs. S4 and S5). Despite these small differences, this visual comparison shows that the areas with expected urban development largely coincide which adds to the credibility of our results.

2.2. Spatial analysis of urban land take

We assessed urban land take for the years 2000 and 2040 as the percentage of all land, all land *suitable* for crop production, and land *available* for crop production, that is characterized as urban land in the respective years. Land suitable for crop production is defined as all land that could be used for rainfed farming. Hence suitable land is a function of the biophysical properties of a location. Land available for crop production is defined as all land that is suitable for crop production, minus land that is legally protected or covered by natural vegetation (Lambin et al., 2013). Other factors, such as property rights and investments also affect land availability, but these factors are not included here due to a lack of data on a global scale. The criteria for land suitable for crop production and land available for crop production are provided in Table 1.

As land change trajectories as well as land system characteristics differ from one region to another, we analyzed urban land take for 24 model regions separately (see Fig. S3). Results are subsequently aggregated to larger regions as well as global totals for presentation purposes.

Table 1
Criteria for land suitable for crop production and land available for crop production (based on Eitelberg et al., 2015). Criteria denote exclusion criteria, and an 'X' denotes exclusion from a particular estimate.

Constraint type	Constraint category *(Full IGBP land cover class names in parentheses when not already specified)*	Land suitable for crop production	Land available for crop production	Reference for exclusion criteria
Land cover constraints	Croplands and cropland/natural vegetation mosaics	–	–	
	Open shrublands, savannas, and grasslands	–	–	
	Closed shrublands and woody savannas	–	X	Cai et al. (2011) and Fritz et al. (2013)
	Forests *(Evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forests)*	–	X	Cai et al. (2011) and Fritz et al. (2013)
	Barren or sparsely vegetated	–	X	Cai et al. (2011) and Fritz et al. (2013)
	Snow and ice	X	X	Cai et al. (2011) and Fritz et al. (2013)
	Urban and built-up	–	–	Cai et al. (2011) and Fritz et al. (2013)
	Permanent wetlands	X	X	Cai et al. (2011) and Fritz et al. (2013)
	Water bodies	X	X	Cai et al. (2011) and Fritz et al. (2013)
Institutional constraints	Protected areas	–	X	Lambin and Meyfroidt (2011)
Biophysical constraints	Aridity index	<0.2	<0.2	Havlík et al. (2011)
	Elevation	>3500 m	>3500 m	Havlík et al. (2011)
	Slope	>30%	>30%	
	Soil clay content	<18%	<18%	Bruinsma, (2003) and Fischer et al., 2000)
	Soil sand content	>65%	>65%	Bruinsma, (2003) and Fischer et al., 2000)
	Soil salt content	High	High	Bruinsma, (2003) and Fischer et al., 2000)
	Gypsiol soils, salic and sodic phase soils, dunes, shifting sands, salt flats, glaciers	X	X	Bruinsma, (2003) and Fischer et al., 2000)
	Length of growing period (with average temperature <5 °C)	<120 days	<120 days	Bruinsma, (2003) and Fischer et al., 2000)
	Average growing season temperature	<10 °C	<10 °C	Havlík et al. (2011)

2.3. Quantification of displacement of crop production from urbanization

Displacement of crop production from urbanization is defined as the amount of crop production that is lost due to the conversion of any other land system into either *Peri-urban and villages systems* or *Urban systems*. The loss of production was calculated as the difference in cropland area between the initial, non-urbanized, land system and the eventual, urbanized, land system, multiplied by the yield of the initial non-urbanized land system. We analyze the loss in crop production relative to the last land system of a pixel before urbanization, to account for land change trajectories. When a pixel starts as extensive cropland in 2000 it can potentially intensify first, and subsequently convert into a *Peri-urban and villages* state. The loss in crop production is then calculated based on the difference between the intensive cropland system, rather than the original extensive cropland system in the year 2000. This displacement of crop production is also calculated for 24 world regions separately, to account for region-specific land system characteristics. Displacement of crop production was subsequently compared to the total increase in crop production between 2000 and 2040.

Demands for both crop production and urban area are defined exogenously for each model region separately. As a consequence, no feedback is included between simulated land-use changes and these demands. Therefore, when the crop production in a region decreases due to urbanization, it needs to increase elsewhere in the same model region in order to satisfy the demand, while no leakage to other world regions is simulated. This increase in production can be achieved through intensification, expansion, or a combination of both.

3. Results

3.1. Urban land take in cropland areas as of 2000 and 2040

As of the year 2000, 271 Mha of earth's surface can be characterized as urban land, which is equal to 2.06% (Table 2), although only 63 Mha of this is actually built-up land. As Fig. 2 shows, there are large regional differences (the values are provided in table S1). Europe, has by far the highest share of urban land, with 8.87% of all land covered by either peri-urban and village systems or urban systems. On the other hand, only 0.39% and 0.47% of Oceania and Sub-Saharan Africa, can be characterized as urban land, respectively. Between 2000 and 2040, the global share of urban land more than doubled, to 621 Mha, or 4.72% of all land area. In 2040 Europe, including Turkey, remains the region with the highest share of urban land, covering 13.72% of its surface. As the population is expected to increase only marginally, urban growth in Europe (which includes Turkey), mainly comes from other processes such as decreasing family sizes, migration, and wealth increases. Oceania remains the region with the lowest share of urban land, covering only 1.21% of its surface. However, the largest relative change was found in Sub-Saharan Africa, where the urban land increased more than six-fold between 2000 and 2040 (Fig. 2 and Table S1).

Globally, the largest share of urban land consists of peri-urban and village systems, while urban systems cover a smaller share. For example, in China, the Middle-East and Northern Africa, and Sub-Saharan Africa, only 15%, 16% and 16% of the urban land consists of strictly urban systems, respectively (see Fig. 2). Between 2000 and 2040 urban systems increase faster than peri-urban and village systems, but this is not true for all world regions. Until 2040, urban development in Asia Pacific and the Middle-East and Northern Africa predominantly takes place in urban systems, while South and Central America, Oceania, North America, and Sub-Saharan Africa see a relatively higher increase in peri-urban and village systems. These different urbanization trajectories are endogenous to the model, as both land systems are driven by one and the same demand.

In the year 2000, 202 Mha of all urban land is located in areas that are suitable for crop production, which is 3.62% of all land that is suitable for crop production (Table 2). Until 2040, this figure more than doubles to 428 Mha, or 7.49% of all land that is suitable for crop production. This observation also holds for each world region separately in 2000, and for each world region except South and Central America in 2040. This outlier is caused both by the large area of suitable land that is covered by tropical forest, and the location of some of the larger cities in this region in areas with a high elevation and steep slopes, which are unsuitable for cultivation according to our assumptions. As of 2000, the region with the largest share of suitable land taken by urbanization is Europe, followed closely by the Middle-East and Northern Africa. Until 2040 the share of suitable land increase most in China and India, where an additional 6.55 and 7.10 percent points of the suitable land are urbanized between 2000 and 2040 (Fig. 2).

When compared against all land that is available for crop cultivation, the land taken by urbanization is 166 Mha, or 4.71% in 2000. Urban land take of available land is similar to urban land take of suitable land, except for those regions that have large shares of forest remaining. This is for example the case in Asia Pacific, where 4.09% of all suitable land and 7.48% of all available land is taken by urbanization, in 2000. As of 2040, the total share of available land that is urbanized increased to 8.84%, globally, with the highest regional values in China (16.4%) and Europe (18.0%).

3.2. Displacement of crop production from urbanization

We simulated land systems changes in response to a demand for crop production, ruminant livestock, and built-up land. In the

Table 2
Urban land take, globally, in 2000 and in 2040. Percentages are relative to the reference indicated in the leftmost column.

Urban land take in		2000 [Mha]	2040 [Mha]	Change 2000–2040 [Mha]
All land	Peri-urban and village systems	213 (1.62%)	467 (3.55%)	+254 (+1.93 pp)
	Urban systems	58 (0.44%)	154 (1.17%)	+97 (+0.73 pp)
	Urban land combined	271 (2.06%)	621 (4.72%)	+350 (+0.55 pp)
All land suitable for crop production	Peri-urban and village systems	159 (2.86%)	320 (5.61%)	+161 (+2.75 pp)
	Urban systems	42 (0.76%)	106 (1.88%)	+64 (+1.12 pp)
	Urban land combined	202 (3.62%)	428 (7.49%)	+227 (+0.83 pp)
All land available for crop production	Peri-urban and village systems	130 (3.70%)	228 (6.38%)	+98 (+2.68 pp)
	Urban systems	35 (1.01%)	87 (2.46%)	+52 (+1.45 pp)
	Urban land combined	166 (4.71%)	315 (8.84%)	+150 (+0.96 pp)

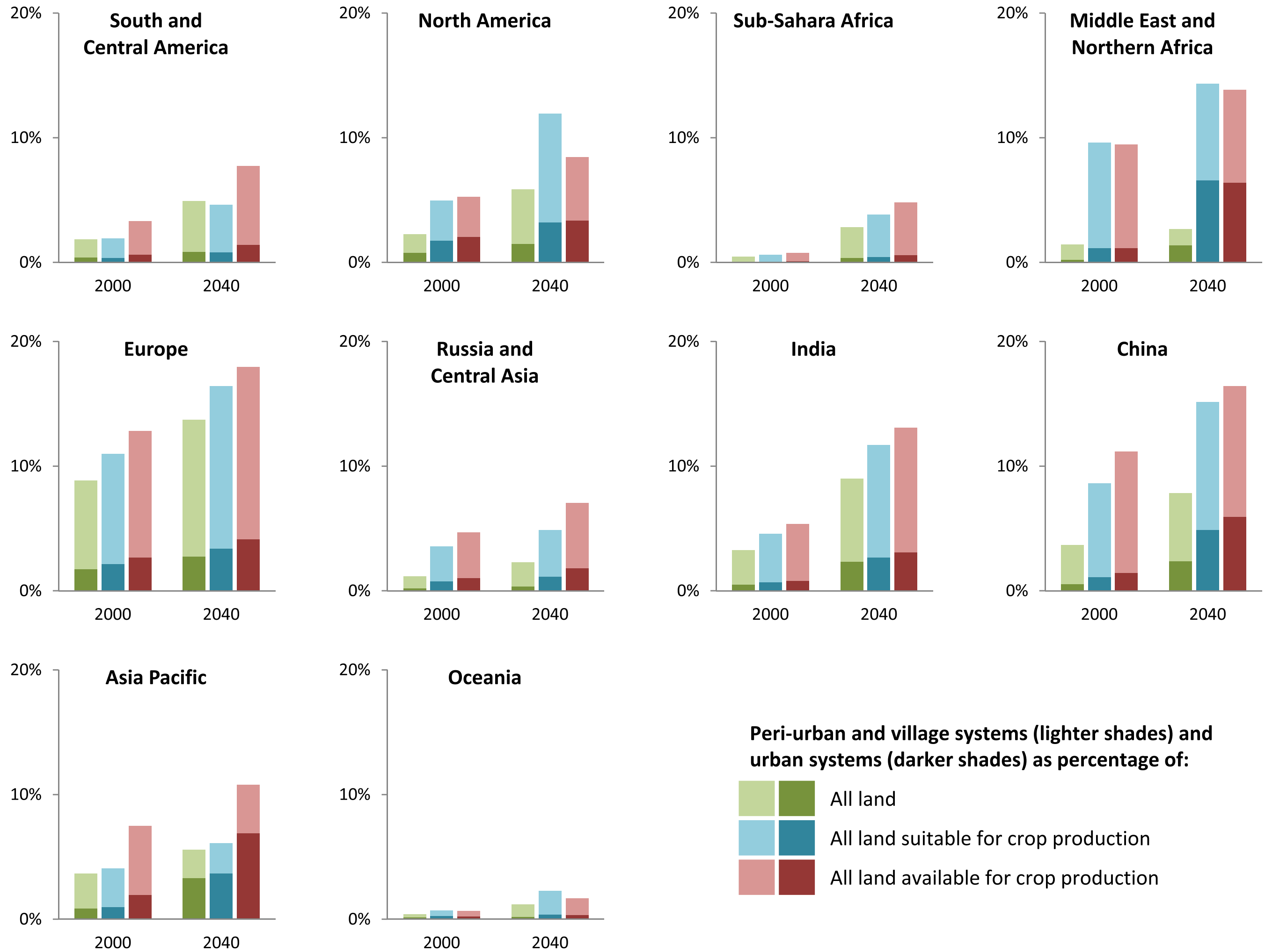

Fig. 2. Urban land take in cropland areas as of 2000 and as of 2040, for major world regions.

competition for land between these demands, urbanization often prevails (Jiang et al., 2013; van Vliet et al., 2015), leading to a conversion of cropland systems and a decrease in food production, locally. This production land displacement from urbanization results in a loss of 65 Mton of crop production between 2000 and 2040, which is about 3.7% of the total increase in food demand in this period (see Table 3). Any losses in crop production due to urbanization are displaced within the same model region, as our modeling framework does not account for leakage effects. However, as the amount of crop displacement is low relative to the total increase in crop production, we assume this simplification is acceptable.

In absolute terms, China and Sub-Saharan Africa face by far the highest displacement of crop production, reaching 13.9 and 12.8 Mton between 2000 and 2040, respectively. In China this is mainly caused by ongoing rural-to-urban migration, leading to new urban development mainly along the eastern coast. This area is also an important area for food production, causing an increased

Table 3
Displacement of food production due to urbanization in major world regions. The percentage is relative to the increase in food production between 2000 and 2040.

World region	Crop production in 2000 [Mton]	Increase in crop production until 2040 [Mton]	Displacement of crop production due to urbanization [Mton]	Displacement of crop production due to urbanization [%]
Central and South America	265.4	277.7	8.0	2,9
North America	506.8	215.4	6.3	2,9
Sub-Saharan Africa	309.0	355.1	12.8	3,6
Middle-East and Northern Africa	66.1	77.6	5.8	7,4
Europe	474.1	70.3	3.4	4,8
Russia/Central Asia	149.8	41.2	0.2	0,5
India	390.5	226.5	7.4	3,3
China	650.5	111.4	13.9	12,5
Asia Pacific	373.1	337.1	6.6	2,0
Oceania	39.6	21.8	0.3	1,3
World	3224.8	1734,0	64,6	3,7%

competition for land (Jiang et al., 2013). In Sub-Saharan Africa, this is largely caused by the expected high population growth rate in the near future, in combination with the low amount of urban land at the start of the simulation. Russia and Central Asia, on the other hand, have the lowest displacement of crop production. This is predominantly a consequence of the low population growth that is expected in this region, leading to a small increase in demand until 2040. Relative to the total increase in crop production, China also has by far the highest displacement, followed by the Middle-East and Northern Africa, which can be explained by their low expected increase in total food production in combination with their relatively rapid urban growth.

The loss in crop production due to urban expansion can be fulfilled elsewhere in the model region by intensification of existing cropland or a conversion of other land into new cropland. From our model, it is not possible to indicate what share of this cropland expansion is caused by crop displacement from urbanization, as there is no direct relation between the production loss from urbanization and the increased production elsewhere. However, we can derive some information from the current distribution of intensification and expansion. In our simulation, 81% of the increase in crop production between 2000 and 2040 was satisfied by intensification of existing cropland, while 19% was satisfied by cropland expansion. This expansion yielded an increase from of 190 Mha of cropland globally, producing an additional 350 Mton of crops per year. Consistently, the 64.6 Mton of crop production that is displaced by urbanization would yield 6.7 Mha new cropland elsewhere. Alternatively, when all displacement of crop production would be attributed to expansion elsewhere, assuming existing cropland would intensify first, a total of 35 Mha of new cropland would be caused by urbanization. In reality, the value will be somewhere in between, and differ from one region to another. For example, a region like Middle East and Northern Africa will mainly satisfy the increased demand for crops by intensification of existing cropland, because there is little possibility for cropland expansion due to the biophysical conditions, while the opposite is true for regions with more space, such as Sub-Sahara Africa.

4. Discussion

4.1. Urban land take and crop displacement due to urbanization

This study shows that globally, 271 Mha of land can be characterized as urban in the year 2000, which is equal to 2.06% of the earth's ice-free surface. Of this urban land, 202 Mha is located in areas that are suitable for crop production, which is equal to 3.62% of all land suitable for crop production. Similarly, 166 Mha of urban land is located in areas that are available for crop production, which is equal to 4.71% of all land that is available for crop production. These numbers confirm our hypothesis that urban land is more than proportionally located in areas that are suitable and available for cropland as well as earlier findings by Avellan et al. (2012) and Bren d'Amour et al. (2016). Hence urban growth and food production are in direct competition for land.

Several other studies have estimated the amount of urban land as of the year 2000 between 0.21% and 2.7% (Potere and Schneider, 2007). The differences between these estimates can for a large part be attributed to the applied definitions of urban land. Lower estimates typically use a narrow definition, such as impervious surfaces (Liu et al., 2014). Higher estimates typically also include vegetated areas, barren land, and water bodies, in addition to the strictly built-up area. Consistently, an assessment based on impervious surface will underestimate the amount of cropland loss from urbanization, as these areas contribute little to food production. Therefore, we adopted a more nuanced land systems approach in this study, which include areas that are not built up in peri-urban and village systems as well as urban systems, thus explaining our results towards the higher side of the range of global estimates.

The influence of the different forms of urbanization is shown in Fig. 3. Urbanization manifests itself in concentrated urban systems in Southeast Asia, for example around Bangkok, Hanoi, Ho Chi Min City (Schneider et al., 2015), while India is characterized mostly by peri-urban and village systems. Because the amount of built-up area per person is likely to depend on the urban structure, peri-urban and village systems and urban systems might yield a

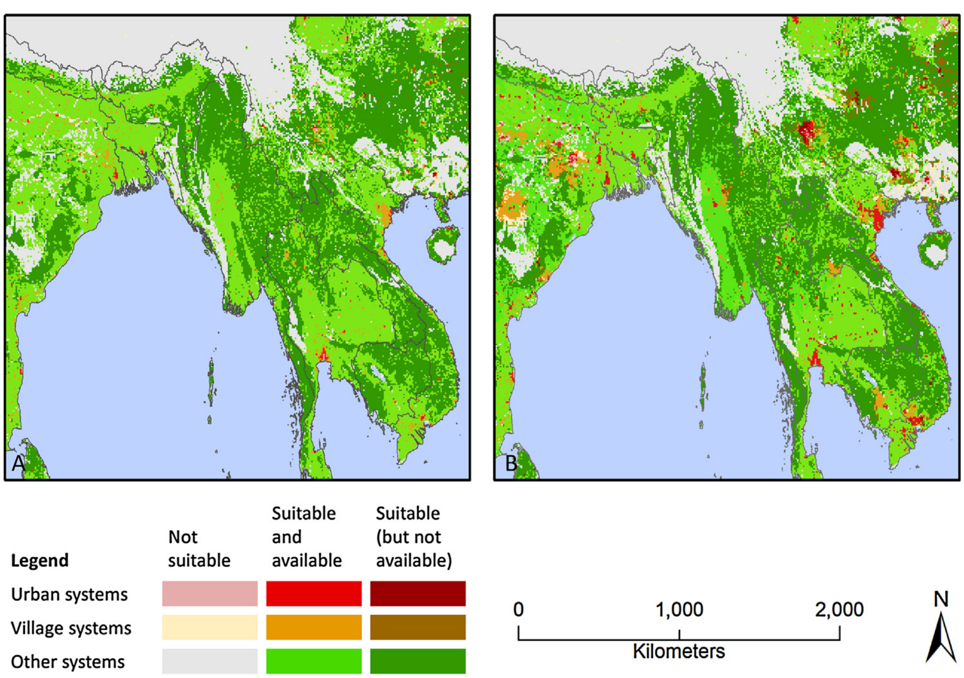

Fig. 3. Urban land in India and Southeast Asia. Map A shows urban land in areas suitable for crop production and areas available for crop production in 2000, map shows urban land in areas suitable for crop production and areas available for crop production in 2040.

different amount of land displacement. In addition to its consequence for food production, different types of urban growth have very different environmental impacts in terms of biodiversity (McKinney, 2008), and local climate impacts (Buyantuyev and Wu, 2010). Refinement and consideration of the different urban forms and the role of these differences for urban lifestyles and land systems could further refine the results and benefit assessments of urban environmental impacts.

We project, in a relatively conservative scenario, that the amount of urban land will increase to 621 Mha in 2040, of which 428 Mha is located in areas that are suitable for crop production, and 315 Mha in areas that are also available for crop production. Hence the competition between urban growth and cropland is likely to continue in the next decades, as urban growth continues to take place more than proportionally in land that is suitable and available for crop production. Other studies show a wide range of results, ranging from 43 Mha to 1257 Mha additional urban land between 2000 and 2030/2040 (see Table 4). However, these differences can for a large part be attributed to different definitions of urban land in these studies, which also explain the range of estimates for the year 2000. When converted to yearly increases, existing estimates yield urban growth rates between 0.8% and 5.2% per year until 2030. This study yields a yearly increase of 2.1% in all urban land combined, which is on the lower side of the range of estimates. One reason for this is that urban growth is in direct competition for space with other land systems in our model, which could push towards more specialized land systems with a higher share of urban land (i.e. urban systems), rather than peri-urban and village systems. At the same time, this range also indicates that urban land take in cropland areas and production displacement from urbanization could be higher than projected in this study.

Our projection yields a total displacement of almost 65 Mtons of crop production between 2000 and 2040, which is slightly more than 2% of the total crop production in the year 2000. In a similar study, Bren d'Amour et al. (2016) estimated the loss of crop production between 2000 and 2030 between 3.4% and 4.2% of the 2000 baseline (expressed in caloric value). This difference largely coincides with the difference in urban growth rate, which is 2.1% for this study and 3.6% for their projections, which are based on Seto et al. (2012a), see Table 4. This difference suggests that the largest uncertainty in the displacement of crop production due to urbanization is in the underlying scenarios for urban growth.

4.2. Implications

Our results show that future urban expansion is primarily expected in areas that are also suitable and available for cropland, thus suggesting a continued competition for land between urban expansion and food production. As urbanization typically prevails in this competition, this will likely yield a displacement of crop production to other areas. In recent years the majority of all new cropland comes at a cost of forests (Gibbs et al., 2010; Hosonuma et al., 2012). This indicates that the land use and land cover changes due to urbanization reach beyond the loss of existing cropland, and also include indirect deforestation as a result of cropland displacement. This displacement can be considered a telecoupling, as the impacts are found in locations that are potentially distant from the place where urbanization takes place (Friis et al., 2015; Seto et al., 2012b). Consistently, any deforestation caused by the compensation for losses in crop production can be considered spillover effects. As international trade in agricultural product continues to increase, such telecoupled effects will become more important in global land change in the near future (Meyfroidt et al., 2010).

On the other hand, the location and type of urban growth can be influenced more than any other land use change by means of land use planning. Land use plans can indicate specific areas where urban areas can expand, thereby for example avoiding the conversion of productive cropland. Such planning measures have already been implemented in China, where the loss of cropland has become a serious threat for food security while urban growth is taking place at unprecedented rates (Lichtenberg and Ding, 2008). However, in many other world regions such policies are not yet implemented, thus leaving a large opportunity to avoid further cropland loss due to urban growth. Similar to the location of new urban areas, planning can also influence the shape of new urban areas, i.e. promoting dense urban areas and avoiding urban sprawl, in order to decrease the total urban land take. Evidence from the Netherlands indicates that such planning measures can reduce urban sprawl, but a comparison with other countries indicates that the efficiency of such planning measures depends highly on the governance of a country or region (Halleux et al., 2012). Moreover, while dense urban development might be preferable from a land take perspective, there is a trade-off with other urban ecosystem services (Larondelle and Haase, 2013; Schneider et al., 2012).

Table 4
Comparison of urban growth scenarios in absolute and relative terms. Projections from Angel et al. (2011) and this study are for 2040, all other projections are for 2030.

Study	Scenario/description	Urban land as of 2000 [10^6 km^2]	Additional urban land until 2030/40 [10^6 km^2]	Yearly increase in urban land [%]
Angel et al. (2011)	0% density decline	0.60	1.05	2.6
	1% density decline	0.60	1.56	3.2
	2% density decline	0.60	2.33	4.0
Lambin and Meyfroidt (2011)	Low estimate	0.66	0.48	1.8
	High estimate	3.51	1.00	0.8
Seto et al. (2011)	A1- MODIS 2001	0.73	2.26	4.8
	A1 –GRUMP 2000	3.52	12.57	5.2
	A1 – GLC 2000	0.31	0.86	4.5
	A2 – MODIS 2001	0.73	1.17	3.2
	A2 – GRUMP 2000	3.52	5.74	3.3
	A2 – GLC 2000	0.31	0.43	3.0
	B1 – MODIS 2001	0.73	1.91	4.4
	B1 – GRUMP 2000	3.52	9.82	4.5
	B1 – GLC 2000	0.31	0.72	4.1
	B2 – MODIS 2001	0.73	1.53	3.8
	B2 – GRUMP 2000	3.52	7.62	3.9
	B2 – GLC 2000	0.31	0.59	3.6
Seto et al. (2012a)	>75% probability	0.65	1.21	3.6
This study	UN medium estimate	2.71	3.50	2.1

Similarly, a discussion about the biodiversity consequences of dense and sparse urban development is emerging, analogous to the discussion about land sharing and land sparing (Lin and Fuller, 2013; Soga et al., 2014). Consequently, when considering land take in combination with urban ecosystem services and biodiversity, it is not yet clear what type of urban development should be promoted by land use planning.

The impact of cropland displacement from urban growth goes beyond that of land use and land cover change strictly, as it affect the livelihoods of the inhabitants of the converted croplands as well as the livelihoods of the inhabitants of new croplands. The civil unrest that started late 2015 in Ethiopia as a consequence of intended urban expansion of the capital, Addis Ababa, is a clear example of this. Local inhabitants protest against governmental plans as the loss of land is a direct threat to their livelihood (Abbink, 2016). Conversely, increasing shares of the Central Rift Valley in Ethiopia are used for crop production due to an increased demand for food. This has major impact on the livelihood of local inhabitants, as these cropland systems are no longer able to also accommodate their pastoral livestock-based livelihoods (Ariti et al., 2015).

Besides the direct impacts of urban growth, in terms of land take of croplands, it also affects cropland systems through a number of other, more indirect relations (Seto and Ramankutty, 2016). Most importantly, a shift from a rural to an urban society has been associated with dietary changes towards more meat, fruits and livestock products (Pingali, 2007), and these changes require a larger amount of land (Kastner et al., 2012). Although urban agriculture offers some opportunities to compensate for these effects, the net effect of multiple interactions between urbanization and the demand for food production is likely to be negative (Badami and Ramankutty, 2015). As a consequence, the increased pressure on land by various demands will probably increase even further than what is calculated based on cropland displacement only.

Acknowledgements

PHV and DAE were supported by the European Research Council grant no. 311819 (GLOLAND). This research contributes to the Global Land Project (www.glp.earth). We would like to thank three anonymous reviewers for the valuable comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2017.02.001.

References

Abbink, J., 2016. Ethiopia's Unrest Sparked by Unequal Development Record [WWW Document]. IPI Glob. Obs. URL https://theglobalobservatory.org/2016/09/ethiopia-protests-amhara-oromiya/ (Accessed 11 November 2016).

Alexander, P., Prestele, R., Verburg, P.H., Arneth, A., Baranzelli, C., Batista e Silva, F., Brown, C., Butler, A., Calvin, K., Dendoncker, N., Doelman, J.C., Dunford, R., Engström, K., Eitelberg, D., Fujimori, S., Harrison, P.A., Hasegawa, T., Havlik, P., Holzhauer, S., Humpenöder, F., Jacobs-Crisioni, C., Jain, A.K., Krisztin, T., Kyle, P., Lavalle, C., Lenton, T., Liu, J., Meiyappan, P., Popp, A., Powell, T., Sands, R.D., Schaldach, R., Stehfest, E., Steinbuks, J., Tabeau, A., van Meijl, H., Wise, M.A., Rounsevell, M.D.A., 2017. Assessing uncertainties in land cover projections. Glob. Chang. Biol. 23 (2), 767–781. doi:http://dx.doi.org/10.1111/gcb.13447.

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision (No. ESA Working paper No. 12-03), Food and Agriculture Organization of the United Nations, Agricultural Economics Division,Rome.

Angel, S., Parent, J., Civco, D.L., Blei, A., Potere, D., 2011. The dimensions of global urban expansion: estimates and projections for all countries, 2000–2050. Prog. Plann. 75, 53–107. doi:http://dx.doi.org/10.1016/j.progress.2011.04.001.

Ariti, A.T., van Vliet, J., Verburg, P.H., 2015. Land-use and land-cover changes in the Central Rift Valley of Ethiopia: assessment of perception and adaptation of stakeholders. Appl. Geogr. 65, 28–37. doi:http://dx.doi.org/10.1016/j.apgeog.2015.10.002.

Avellan, T., Meier, J., Mauser, W., 2012. Are urban areas endangering the availability of rainfed crop suitable land? Remote Sens. Lett. 3, 631–638. doi:http://dx.doi.org/10.1080/01431161.2012.659353.

Badami, M.G., Ramankutty, N., 2015. Urban agriculture and food security: a critique based on an assessment of urban land constraints. Glob. Food Sec. 4, 8–15. doi:http://dx.doi.org/10.1016/j.gfs.2014.10.003.

Bagan, H., Yamagata, Y., 2014. Land-cover change analysis in 50 global cities by using a combination of Landsat data and analysis of grid cells. Environ. Res. Lett. 9, 064015. doi:http://dx.doi.org/10.1088/1748-9326/9/6/064015.

Bouwman, A.F., Kram, T., Klein Goldewijk, K., 2006. Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven, Netherlands.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C., 2016. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. 201606036. doi:http://dx.doi.org/10.1073/pnas.1606036114.

Bruinsma, J. (Ed.), 2003. World Agriculture: Towards 2015/2030. Earthscan, London, UK.

Buyantuyev, A., Wu, J., 2010. Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. Landsc. Ecol. 25, 17–33. doi:http://dx.doi.org/10.1007/s10980-009-9402-4.

Cai, X., Zhang, X., Wang, D., 2011. Land availability for biofuel production. Environ. Sci. Technol. 45, 334–339. doi:http://dx.doi.org/10.1021/es103338e.

del Mar López, T., Aide, T.M., Thomlinson, J.R., 2001. Urban expansion and the loss of prime agricultural lands in Puerto Rico. AMBIO: A J. Hum. Environ. 30, 49–54. doi:http://dx.doi.org/10.1579/0044-7447-30.1.49.

Eitelberg, D.A., van Vliet, J., Verburg, P.H., 2015. A review of global potentially available cropland estimates and their consequences for model-based assessments. Glob. Change Biol. 21, 1236–1248. doi:http://dx.doi.org/10.1111/gcb.12733.

Eitelberg, D.A., van Vliet, J., Doelman, J.C., Stehfest, E., Verburg, P.H., 2016. Demand for biodiversity protection and carbon storage as drivers of global land change scenarios. Glob. Environ. Change 40, 101–111. doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.06.014.

Ellis, E.C., Ramankutty, N., 2008. Putting people in the map: anthropogenic biomes of the world. Front. Ecol. Environ. 6, 439–447. doi:http://dx.doi.org/10.1890/070062.

FAO, 2007. Gridded Livestock of the World. FAO, Rome, Italy.

Fischer, G., Velthuizen, H., Nachtergale, F., 2000. Global Agro-Ecological Zones Assessment: Methodology and Results. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Friis, C., Nielsen, J.Ø., Otero, I., Haberl, H., Niewöhner, J., Hostert, P., 2015. From teleconnection to telecoupling: taking stock of an emerging framework in land system science. J. Land Use Sci. 1–23 doi:http://dx.doi.org/10.1080/1747423x.2015.1096423.

Fritz, S., See, L., van der Velde, M., Nalepa, R.A., Perger, C., Schill, C., McCallum, I., Schepaschenko, D., Kraxner, F., Cai, X., Zhang, X., Ortner, S., Hazarika, R., Cipriani, A., Di Bella, C., Rabia, A.H., Garcia, A., Vakolyuk, M., Singha, K., Beget, M.E., Erasmi, S., Albrecht, F., Shaw, B., Obersteiner, M., 2013. Downgrading recent estimates of land available for biofuel production. Environ. Sci. Technol. 47 (3), 1688–1694. doi:http://dx.doi.org/10.1021/es303141h.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980 and 1990. Proc. Natl. Acad. Sci. U. S. A. 107, 16732–16737. doi:http://dx.doi.org/10.1073/pnas.0910275107.

Halleux, J.-M., Marcinczak, S., van der Krabben, E., 2012. The adaptive efficiency of land use planning measured by the control of urban sprawl. The cases of the Netherlands, Belgium and Poland. Land Use Policy 29, 887–898. doi:http://dx.doi.org/10.1016/j.landusepol.2012.01.008.

Hansen, M.C., Stehman, S.V., Potapov, P.V., 2010. Quantification of global gross forest cover loss. Proc. Natl. Acad. Sci. 107, 8650–8655.

Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S., De Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. doi:http://dx.doi.org/10.1016/j.enpol.2010.03.030.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A., Romijn, E., 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environ. Res. Lett. 7, 044009. doi:http://dx.doi.org/10.1088/1748-9326/7/4/044009.

Jiang, L., O'Neill, B.C., 2015. Global urbanization projections for the shared socioeconomic pathways. Glob. Environ. Change 42, 193–199. doi:http://dx.doi.org/10.1016/j.gloenvcha.2015.03.008.

Jiang, L., Deng, X., Seto, K.C., 2013. The impact of urban expansion on agricultural land use intensity in China. Land Use Policy 35, 33–39. doi:http://dx.doi.org/10.1016/j.landusepol.2013.04.011.

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109, 6868–6872. doi:http://dx.doi.org/10.1073/pnas.1117054109.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. U. S. A. 108, 3465–3472. doi:http://dx.doi.org/10.1073/pnas.1100480108.

Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D.C., Rudel, T.K., Gasparri, I., Munger, J., 2013. Estimating the world's potentially available cropland using a bottom-up approach. Glob. Environ. Change 23, 892–901. doi:http://dx.doi.org/10.1016/j.gloenvcha.2013.05.005.
Larondelle, N., Haase, D., 2013. Urban ecosystem services assessment along a rural-urban gradient: a cross-analysis of European cities. Ecol. Indic. 29, 179–190. doi: http://dx.doi.org/10.1016/j.ecolind.2012.12.022.
Lichtenberg, E., Ding, C., 2008. Assessing farmland protection policy in China. Land Use Policy 25, 59–68. doi:http://dx.doi.org/10.1016/j.landusepol.2006.01.005.
Lin, B.B., Fuller, R.A., 2013. Sharing or sparing? How should we grow the world's cities?. J. Appl. Ecol. 50, 1161–1168. doi:http://dx.doi.org/10.1111/1365-2664.12118.
Liu, J., Zhan, J., Deng, X., 2005. Spatio-temporal patterns and driving forces of urban land expansion in China during the economic reform era. AMBIO: A J. Hum. Environ. 34, 450–455. doi:http://dx.doi.org/10.1579/0044-7447-34.6.450.
Liu, Z., He, C., Zhou, Y., Wu, J., 2014. How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. Landsc. Ecol. 29, 763–771. doi:http://dx.doi.org/10.1007/s10980-014-0034-y.
Lu, Y., Jenkins, A., Ferrier, R.C., Bailey, M., Gordon, I.J., Song, S., Huang, J., Jia, S., Zhang, F., Liu, X., Feng, Z., Zhang, Z., 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1, e1400039. doi:http://dx.doi.org/10.1126/sciadv.1400039.
McKinney, M.L., 2008. Effects of urbanization on species richness: a review of plants and animals. Urban Ecosyst. 11, 161–176. doi:http://dx.doi.org/10.1007/s11252-007-0045-4.
Meyfroidt, P., Rudel, T.K., Lambin, E.F., 2010. Forest transitions, trade, and the global displacement of land use. Proc. Natl. Acad. Sci. 107, 20917–20922. doi:http://dx.doi.org/10.1073/pnas.1014773107.
Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, n/a–n/a. doi:http://dx.doi.org/10.1029/2007gb002947.
Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: a spatial analysis. Agric. Syst. 103, 316–326. doi:http://dx.doi.org/10.1016/j.agsy.2010.02.004.
Nkeki, F.N., 2016. Spatio-temporal analysis of land use transition and urban growth characterization in Benin metropolitan region, Nigeria. Remote Sens. Appl. Soc. Environ. 4, 119–137. doi:http://dx.doi.org/10.1016/j.rsase.2016.08.002.
Pandey, B., Seto, K.C., 2015. Urbanization and agricultural land loss in India: comparing satellite estimates with census data. J. Environ. Manage. 148, 53–66. doi:http://dx.doi.org/10.1016/j.jenvman.2014.05.014.
Pingali, P., 2007. Westernization of Asian diets and the transformation of food systems: implications for research and policy. Food Policy 32, 281–298. doi: http://dx.doi.org/10.1016/j.foodpol.2006.08.001.
Plieninger, T., Bieling, C., Fagerholm, N., Byg, A., Hartel, T., Hurley, P., López-Santiago, C.A., Nagabhatla, N., Oteros-Rozas, E., Raymond, C.M., van der Horst, D., Huntsinger, L., 2015. The role of cultural ecosystem services in landscape management and planning. Curr. Opin. Environ. Sustain. 14, 28–33. doi:http://dx.doi.org/10.1016/j.cosust.2015.02.006.
Potere, D., Schneider, A., 2007. A critical look at representations of urban areas in global maps. GeoJournal 69, 55–80. doi:http://dx.doi.org/10.1007/s10708-007-9102-z.
Prestele, R., Alexander, P., Rounsevell, M., Arneth, A., Calvin, K., Doelman, J., Eitelberg, D., Engström, K., Fujimori, S., Hasegawa, T., Havlik, P., Humpenöder, F., Jain, A., Krisztin, T., Kyle, P., Meiyappan, P., Popp, A., Sands, R., Schaldach, R., Schüngel, J., Stehfest, E., Tabeau, A., Van Meijl, H., 2016. Hotspots of uncertainty in land use and land cover change projections: a global scale model comparison. Glob. Chang. Biol. 22, 3967–3983. doi:http://dx.doi.org/10.3837/tiis.0000.00.000.
Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob. Biogeochem. Cycles 22 doi:http://dx.doi.org/10.1029/2007gb002952.
Schneider, A., Friedl, M.A., Potere, D., 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 15 (4), 519–541. doi:http://dx.doi.org/10.1088/1748-9326/4/4/044003.
Schneider, A., Logan, K.E., Kucharik, C.J., 2012. Impacts of urbanization on ecosystem goods and services in the U.S. Corn Belt. Ecosystems 15, 519–541. doi:http://dx.doi.org/10.1007/s10021-012-9519-1.
Schneider, A., Mertes, C.M., Tatem, A.J., Tan, B., Sulla-Menashe, D., Graves, S.J., Patel, N.N., Horton, J.A., Gaughan, A.E., Rollo, J.T., Schelly, I.H., Stevens, F.R., Dastur, A., 2015. A new urban landscape in East–Southeast asia, 2000–2010. Environ. Res. Lett. 10, 034002. doi:http://dx.doi.org/10.1088/1748-9326/10/3/034002.
Seto, K.C., Ramankutty, N., 2016. Hidden linkages between urbanization and food systems. Science 352 (80), 943–945. doi:http://dx.doi.org/10.1126/science.aaf7439.
Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PLoS One 6, e23777. doi:http://dx.doi.org/10.1371/journal.pone.0023777.
Seto, K.C., Guneralp, B., Hutyra, L.R., 2012a. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088. doi:http://dx.doi.org/10.1073/pnas.1211658109.
Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012b. Urban land teleconnections and sustainability. Proc. Natl. Acad. Sci. U. S. A. 109, 7687–7692. doi:http://dx.doi.org/10.1073/pnas.1117622109.
Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E., Smith, D.R., 2005. Impacts of impervious surface on watershed hydrology: a review. Urban Water J. 2, 263–275. doi:http://dx.doi.org/10.1080/15730620500386529.
Soga, M., Yamaura, Y., Koike, S., Gaston, K.J., 2014. Land sharing vs. land sparing: does the compact city reconcile urban development and biodiversity conservation? J. Appl. Ecol. 51, 1378–1386. doi:http://dx.doi.org/10.1111/1365-2664.12280.
Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, M., Prins, A., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model Description and Policy Applications. PBL Netherlands Environmental Assessment Agency, The Hague.
Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240 (4857), 1285–1293. doi:http://dx.doi.org/10.1126/science.3287615.
Thebo, A.L., Drechsel, P., Lambin, E.F., 2014. Global assessment of urban and peri-urban agriculture: irrigated and rainfed croplands. Environ. Res. Lett. 9, 114002. doi:http://dx.doi.org/10.1088/1748-9326/9/11/114002.
United Nations, 2009. Department of economic and social affairs, P.D. World Population Prospects: The Revision, .
United Nations, 2014. Department of economic and socal affairs, P. division. World Urbanization Prospects: the 2014 Revision, (ST/ESA/SER.A/352).
van Asselen, S., Verburg, P.H., 2012. A land system representation for global assessments and land-use modeling. Glob. Chang. Biol. 18, 3125–3148. doi: http://dx.doi.org/10.1111/j.1365-2486.2012.02759.x.
van Asselen, S., Verburg, P.H., 2013. Land cover change or land-use intensification: simulating land system change with a global-scale land change model. Glob. Change Biol. 19, 3648–3667. doi:http://dx.doi.org/10.1111/gcb.12331.
van Vliet, J., Naus, N., van Lammeren, R.J.A., Bregt, A.K., Hurkens, J., van Delden, H., 2013. Measuring the neighbourhood effect to calibrate land use models. Comput. Environ. Urban Syst. 41, 55–64. doi:http://dx.doi.org/10.1016/j.compenvurbsys.2013.03.006.
van Vliet, J., de Groot, H.L.F., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landsc. Urban Plan. 133, 24–36. doi:http://dx.doi.org/10.1016/j.landurbplan.2014.09.001.
Verburg, P.H., van Asselen, S., van der Zanden, E.H., Stehfest, E., 2013. The representation of landscapes in global scale assessments of environmental change. Landsc. Ecol. 28, 1067–1080. doi:http://dx.doi.org/10.1007/s10980-012-9745-0.
Woltjer, G.B., Kuiper, M., Kavallari, A., van Meijl, H., Powell, J., Rutten, M., Shutes, L., Tabeau, A., 2014. The MAGNET Model – Module Description. LEI Wageningen UR, Wageningen.
Zasada, I., Berges, R., Hilgendorf, J., Piorr, A., 2013. Horsekeeping and the peri-urban development in the Berlin Metropolitan Region. J. Land Use Sci. 8, 199–214. doi: http://dx.doi.org/10.1080/1747423X.2011.628706.