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Long-term projections of global urban expansion's impact on both cropland and potential crop production

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Abstract

The loss of cropland area for food production is one of the main factors that affects food insecurity for the future of the world. In addition to the changes in cultivation environments due to desertification, the diversion of agricultural land to urban areas because of socioeconomic activity is also a cause of cropland loss. Japan's experience shows that cropland is used for road-building and industrial and residential development and that it shrinks rapidly during the process of industrialization if population density is already very high before industrialization begins. If China, India and other developing countries follow the same developmental path, global food insecurity will increase in the future. On the other hand, the impact of urbanization on food production might not be important because the current share of urban area on the Earth's land surface is very small. In the present study, the urban areas of 185 countries have been projected from 2000 to 2100 based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), using data from four previous studies (Columbia University (GRUMP); Food and Agriculture Organization of the United Nations; Boston University (MOD12); World Bank) of global urban areas. Losses to both existing cropland and potential crop production due to urban expansion have been predicted based on the assumption that the future urbanization potential in rural areas is proportional to its population density in 2000. The present study yields the following results: (1) based on a review of previous studies, the global urban area in 2000 was estimated at between 0.4 million km^2 and 3.51 million km^2; (2) in the present study, the global urban area in 2000 has been estimated at 1.12 million km^2 after adjusting the urban area denoted by MOD12 so that its urban population is in agreement with United Nations urban population statistics (MOD12-a); (3) the global urban areas in MOD12-a will expand to 4.82 million km^2 in 2100 under the A2r scenario, 3.17 million km^2 in 2070 under the B1 scenario, and 4.13 million km^2 in 2100 under the B2 scenario; (4) the losses to global cropland areas in 2100 will reach 1.8 million km^2 in the A2r scenario, 1.0 million km^2 in the B1 scenario, and 1.39 million km^2 in the B2 scenario; and (5) consequently, potential crop production in 2100 will decrease by 15.8 percent in the A2r scenario, 8.3 percent in the B1 scenario, and 12.1 percent in the B2 scenario compared to figures from 2000. At the country level, it has been shown that reduction rates will be remarkably high in Asian developing countries, namely Pakistan, Bangladesh, Indonesia, the Philippines, China, Vietnam, Cambodia, India, and Myanmar.

Keywords: urbanization, cropland diversion, food insecurity, land cover, IPCC SRES

1. Introduction

Although future global food insecurity will be affected by various factors, such as population growth, the expansion of poverty, and climate change, the loss of cropland areas for food production is one of the main factors involved. In addition to changes in cultivation environments due to desertification, the diversion of agricultural land to urban areas causes cropland reduction. Japan's experience shows that cropland is used for road-building and industrial and residential development and shrinks rapidly during the process of industrialization if population density is already very high before industrialization begins. If China, India and other developing countries follow the same developmental path, global food insecurity will increase in the future, as shown in Brown [1]. The size of the land area appropriated for urban use is less important than the way cities expand because global urban expansion takes up much less land than do activities that produce resources for consumption such as food, building materials or mined natural resources [2]. The impact of urban expansion on crop production depends on the way that cities expand because many cities are situated in the heart of rich agricultural areas. Furthermore, decreases in crop production might become larger in some countries or regions, while the impact of urban expansion on crop production might be small worldwide.

This controversy is caused by different definitions of “urban” in different countries and by defects in global urban area statistics. In the present study, the current global urban areas are first estimated and then compared with those listed in previous studies. Then, ranges of future urban areas are projected in combination with socioeconomic scenarios. Finally, projected decreases in potential crop production are calculated based on the loss of existing croplands and their geographical distributions. Although the Food and Agriculture Organization of the United Nations (FAO) reports that there is enough room to expand cropland [3], the expansion of cropland causes deforestation, especially in developing countries. Therefore, it is assumed that cropland areas will not expand in the present study.

2. Data and Methodology

A flow chart representing the methodology of the present study is shown in Figure 1. First, we review the estimates of current urban areas worldwide as depicted in previous studies: the Global Rural-Urban Mapping Project (GRUMP) at Columbia University [4], Mapping Global Urban and Rural Population Distribution by FAO [5], Land cover and Land cover Dynamics Products (MOD12) by Boston University [6], and the Dynamics of Global Urban Expansion by the World Bank [7]. Next, the potential urban area (buildable area) of each country is estimated based on the United Nations data on protected areas of the world [8] and the maximum slope of urban area in MOD12, assuming that the oecumene (or the inhabited areas of the world) will be restricted to the present population distribution area in the global population database (LandScan) according to Oak Ridge National Laboratory (ORNL) [9]. In addition, the urban area in MOD12 must be adjusted in such a way that the urban population equals the United Nations population estimates from the year 2000 [10] in each country. From here on, we refer to this modified MOD12 data as MOD12-a.

After modifying the urban area, we project urban expansion in 185 countries from 2000 to 2100. First, the elasticities of urban areas to per capita GDP and potential urban area per person are estimated using the data set for each variable for the year 2000. Then, using the elasticities, future urban expansion in each country is calculated based on the three socioeconomic scenarios from the Intergovernmental Panel on Climate Change (IPCC) [11] subject to potential urban area.

Finally, future spatial distributions of urban area and cropland are estimated in combination with the estimated total urban expansion and spatial population distribution (LandScan). Then, future losses of potential crop production are calculated for each country using the data set of the spatial distribution of maximum yield from the GAEZ analysis [12].

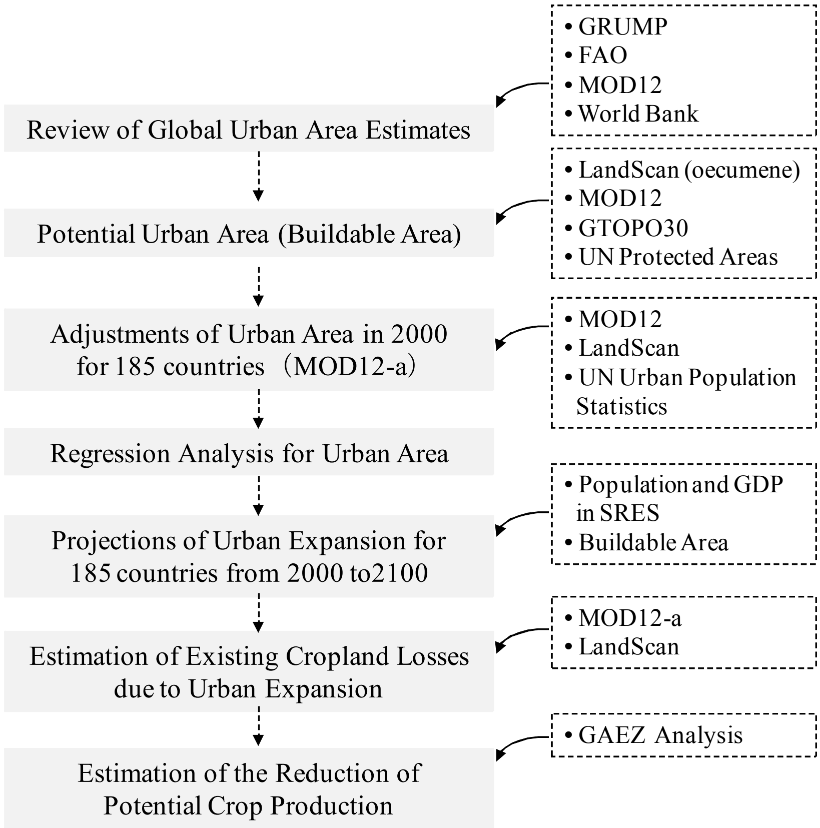


Figure 1. Framework of the methodology for estimating crop production reduction due to urbanization

The main assumptions of the present study are as follows. Although many economic factors can affect the future expansion of urban area, such as land rent, per capita GDP is the only factor considered in the present study. As for crop production, potential production rather than real production is used to calculate future yield growth. The potential for urbanization in a certain rural (non-urban) area is assumed to be proportional to its present population density. Therefore, long-term changes in regional urbanization potential that will be caused by global warming and other similar factors are not considered in the present study. These changes are left for future studies to consider.

3. Review of present urban area estimates in the world

While the urban population statistics for 228 countries have been published by the United Nations [10], statistics for global urban areas have not been reported so far. Definitions of urban areas are different from country to country and take into account various criteria: administrative districts, population, economic characteristics, functional nature of urban areas (pavement, water supply and sewerage systems, electric lights), etc.

For this reason, we first review previous studies related to the estimation of global urban areas, summarizing the time period analyzed, methodologies used, and ranges of urban areas predicted. In the analysis that follows, raster data (MOD12 and GRUMP) are aggregated on country or region levels for comparison with data of other studies based on the Coastline and International Boundaries of the World map (Vmap0) by the FAO [13], which was originally a vector map and was converted to a raster grid cell format with resolution of 30 arc seconds.

3.1. Global Rural-Urban Mapping Project (GRUMP) data set by Columbia University

GRUMP is a global geographical data set of urban areas and population developed by the Columbia University Earth Institute's Center for International Earth Science Information Network (CIESIN) with resolution of 30 arc seconds. Although the timeframe of the estimation is not specified clearly for the data on urban areas, population distributions are estimated for 1990, 1995, and 2005 and are consistent with the United Nations population statistics.

Global urban area data sets are developed from the following four data sources: (1) the human settlements database detailing settlements of 1,000 persons or more, where each settlement is spatially represented as a point; (2) NOAA's night-time lights data set from DMSP-OLS for the period from 1 October 1994 to 30 April 1995; (3) the Digital Chart of the World's Populated Places (DCW), an ESRI product that contains urbanized areas (built-up areas) of the world represented as polygons (1993 version); and (4)

Tactical Pilotage Charts (TPC): standard charts produced by the Australian Defense Imagery and Geospatial Organization. The night-time lights are used as a baseline for estimating human activities on a global scale. Then, polygons that do not intersect with any existing light are added from other sources (DCW and TPC). For human settlement points without polygons, areas are estimated based on a relationship between the latter and population size, and circles centered on the points are added to the existing polygons to visually capture complete urban area for each country [14].

Two problems arise when the night-time lights data set is used as a baseline for identifying urban area: the insufficient detection of small settlements and the blooming effect. Although the former has been reduced by using DCW and TPCs polygons, the blooming effect remains unaddressed. The blooming effect is the overestimation of real urban areas and is dependent on the intrinsic characteristics of the sensor [14].

Table 1. Comparison of urban areas and potential urban area (buildable area) by UN regions

Continent	Region	Urban Area (1000 km^2)				Buildable Area (1000km^2)
		GRUMP	FAO	MOD12	MOD12-a	
Africa	Eastern Africa	32.2	44.8	10.1	21.1	4,981.4
	Middle Africa	16.7	17.1	3.5	7.9	4,215.3
	Northern Africa	82.8	55.5	15.9	22.7	2,207.1
	Southern Africa	50.0	21.3	10.5	13.2	985.2
	Western Africa	40.1	60.4	13.6	23.9	3,494.8
Americas	Caribbean	30.3	20.3	1.2	4.2	136.5
	Central America	122.7	44.8	8.8	19.6	1,537.3
	Northern America	886.7	292.4	124.8	194.9	2,533.6
	South America	375.2	425.8	42.3	86.0	8,001.1
Asia	Eastern Asia	297.3	266.4	107.3	120.8	5,785.0
	Japan	103.2	26.4	52.3	52.3	264.0
	South-central Asia	350.8	153.7	85.7	99.8	5,879.1
	South-eastern Asia	97.1	83.9	12.3	30.0	2,517.9
	Western Asia	145.1	74.2	28.0	40.2	1,583.6
Europe	Eastern Europe	301.3	217.9	68.2	123.0	4,467.7
	Northern Europe	156.7	89.7	21.4	55.7	655.6
	Southern Europe	194.4	49.4	49.1	58.8	1,046.3
	Western Europe	179.9	225.3	53.0	127.9	904.1
Oceania	Australia and New Zealand	44.6	42.1	9.1	16.6	606.2
	Melanesia	3.0	2.0	0.1	0.3	282.4
	Developing Countries	1,644.3	1,270.3	339.3	489.9	41,610.6
	Developed Countries	1,866.8	943.2	377.9	629.2	10,477.5
	World Total	3,511.1	2,213.5	717.2	1,119.1	52,088.2
	Percentage of world's land area	2.6	1.6	0.5	0.8	38.7

Consequently, global urban area in the GRUMP data set is 3.51 million km^2, which is 2.6 percent of the world's land area excluding Antarctica. The GRUMP data set indicates the largest urban area of the four previous works (Table 1).

3.2. Mapping global urban and rural population distribution by the FAO

This report was published to explore the use of high-resolution geo-referenced data and GIS-based analysis techniques to pinpoint the precise conditions underlying poverty and hunger in the world. Four primary sources are used to create the databases for gridded urban, rural and rural settlement population: (1) LandScan 2002 as the reference database for population distribution, (2) Nighttime Lights of the World 2000 to identify the urban areas, (3) UN population data for each country for the year 2000, and (4) the UN (DPKO/UNCS) International Boundaries/Coastlines map for 2004 to determine the country boundaries and coastlines [5].

The estimation procedure is as follows. First, the global population distribution for the year 2000 is established using the LandScan 2002 data set and the United Nations population statistics for the year 2000. This population distribution is generated at a resolution of 5 arc minutes in accordance with that of the environmental data set, while LandScan features a 30 arc second resolution. Neither countries with areas less than 3,000 square kilometers nor countries with a UN total population figure less than 500,000 are included in the analysis because of insufficient accuracy. As a result, 154 countries are included in the analysis.

Next, urban areas are determined using the population distribution and Nighttime Lights. Each populated grid is allocated to urban areas with a light intensity higher than the threshold, which is determined in such a way that the urban population is equal to that reflected in the UN urban population statistics in 2000 for each country. Using Nighttime Lights tends to lead one to overestimate the actual urban areas because of the blooming effect. To reduce the blooming effect, average urban population density is calculated, and all of the grids in which the number of people is less than ten percent of this value are reclassified as rural [5].

Consequently, urban area is estimated at 2.21 million km^2, which is 1.6 percent of the world's land area excluding Antarctica. The FAO data set indicates the second largest urban areas of the four previous works (Table 1).

3.3. Land cover and Land cover Dynamics Products (MOD12) from Boston University

MOD12 is a global land cover map with resolution of 30 arc seconds that was developed from MODIS (Moderate Resolution Imaging Spectrometer) data from the period 1 January 2001 to 31 December 2001. MODIS is a key instrument aboard the Terra (EOS AM) satellite, which was launched by NASA in December 1999 and provides low-resolution satellite images from 250 to 1000 meters. The images are used to measure changes in the Earth's surface including land cover and vegetation due to its short recurrence period and wide scope of scanning [15] [16].

MOD12 is the 12^{th} product made from MODIS data and provides information on land cover/land cover changes. In MOD12Q1 (global land cover), used in the present study, land cover classification is carried out using a supervised classification approach and a neural network following the International Geosphere-Biosphere Program (IGBP) scheme (Table 2).

Based on the evaluation of four existing land cover maps for Eurasia (GLC2000, MOD12, UMD, and GLCC), the levels of agreement between the validation information and the land cover maps are at 55 percent for GLC2000, 58 percent for MOD12, 54 percent for UMD, and 50 percent for GLCC. MOD12 features somewhat better agreement than the other maps [17].

The urban areas in MOD12 are estimated to make up 0.72 million km^2, which is 0.5 percent of the world's land area excluding Antarctica (Table 1). Unlike the figures from the GRUMP and FAO data sets, the urban population in MOD12 is not consistent with the UN urban population statistics.

Table 2. MOD12 land cover classification (IGBP class scheme)

Class	Class Name
0	Water
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forests
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetlands
12	Croplands
13	Urban and Built-Up
14	Cropland/Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated

3.4. The Dynamics of Global Urban Expansion by the World Bank

This report examines the dynamics of global urban expansion by defining a universe of 3,943 world cities with population in excess of 100,000, drawing a stratified global sample of 90 cities from this universe. The objective of the analysis is not to estimate cities' administrative areas but rather to measure actual built-up areas and their population densities. For this purpose, population data and satellite images for the years 1990 and 2000 are obtained and analyzed. The Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper-Plus (ETM) data are selected as the basis for image analysis and land cover classification. The resolution of the image pixels is 28.5 meters, which is significantly higher than that indicated in the other previous studies mentioned above. Therefore, the urban areas do not include many of the open spaces that are largely contained within the built-up areas of the city, such as parks, golf courses, and simple green space. Eventually, averages for built-up areas and population density are estimated for nine regions in the world from the weighted averages of the 90 cities [7].

In this report, a time series analysis of urban areas was conducted for the same city samples, which is something that was not done in the other previous studies. This analysis shows that the built-up areas in all regions increased from 1990 to 2000, that the population density in all regions has continued to decrease and that its global average declines at an annual rate of 1.7 percent from 1990 to 2000. The total urban area is estimated to be 0.41 million km^2, which is 0.3 percent of the world's land area excluding Antarctica. This data set yields the smallest urban area of the four previous works (Table 3).

Table 3. World Bank estimates of built-up area totals and built-up area per person by region

Region	Built-up Area (1000 km^2)			Average Built-up Area per Person (m^2)		
	1990	2000	Annual % Change	1990	2000	Annual % Change
East Asia & the Pacific	21.9	43.9	7.2	65	105	5.1
Europe	66.6	81.4	2.0	190	230	1.9
Latin America & the Caribbean	33.7	42.6	2.4	145	145	0.3
Northern Africa	4.5	5.9	2.8	100	110	0.8
Other Developed Countries	120.8	159.6	2.8	360	435	2.0
South & Central Asia	15.5	24.2	4.6	55	75	2.7
Southeast Asia	3.6	6.7	6.4	40	60	4.4
Sub-Saharan Africa	19.1	28.8	6.1	105	150	3.6
Western Asia	12.7	15.8	2.2	155	170	1.0
Developing Countries	145.8	206.9	3.6	105	125	1.7
Industrialized Countries	152.5	202.1	2.9	280	355	2.3
World Total	298.3	409.0	3.2	154	183	1.7
Percentage of world land area	0.2	0.3	—	—	—	—

Note: Based on weighted averages of the 90-city sample.

4. Delineating potential urban areas

The next step is to delineate potential urban areas (buildable areas) for each country. The oecumene, or the inhabited areas of the world, has extended into non-oecumene areas with the development of civilization and population growth. These days, non-oecumene areas are limited only to nival, desert and highland climate zones, whose boundaries are in accordance with those of crop production. While the oecumene is dependent on natural conditions, there are some inhabited areas in arid regions where water is supplied from underground or by desalting seawater [18].

As shown in Figure 2, potential urban areas are considered a part of the oecumene and are seen as dependent on geographical characteristics such as terrain (slope), climate condition, water availability, and risk associated with natural disasters. For example, based on the comparison of urban areas in MOD12 with Koeppen's Climate Classification, 55 percent of world urban areas exist in a temperate climate, 21 percent in a subpolar climate, 15 percent in an arid climate, and 9 percent in a tropical climate [19]. Regarding water availability, we note that although global groundwater maps are distributed by UNESCO, those maps are not available in geographic information systems [20].

Therefore, in the present study, it is assumed that future inhabited areas will be restricted to the current populated areas estimated in LandScan 2007. Next, potential urban areas are chosen from within those areas on the condition that the average slope of the area is smaller than the maximum slope of urban areas in MOD12. To determine the maximum slope of urban areas for a given country, cumulative values for urban areas are calculated in ascending order of slope. Then the maximum slope is determined when cumulative value reaches 99 percent of total urban areas. The slope of each grid is calculated from the GTOPO30 global digital elevation model (DEM) with resolution of 30 arcs second, which was developed by the U.S. Geological Survey [21]. As for water availability, it is assumed that there is enough water in the present inhabited areas for developing cities.

Potential urban areas organized by UN region are shown in Table 1. The global potential urban areas comprise 52.08 million km^2 and account for 38.7 percent of world's land area excluding Antarctica and 95 percent of present inhabited areas (54.85 million km^2).

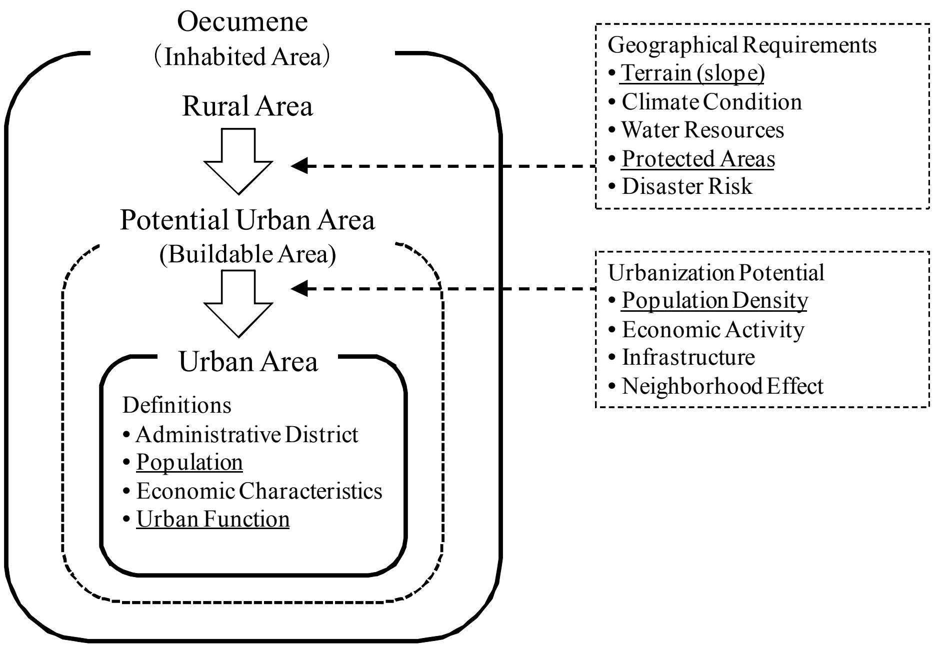


Figure 2. Processes of urbanization assumed in the present study

5. Adjustment of urban areas for the year 2000 (MOD12-a)

As mentioned above, the GRUMP figures for urban areas are considered to be overestimates due to the blooming effect. The FAO geographical data set is not available at a high resolution. Although the actual urban areas are estimated in the World Bank report, they are based on the 90 sample cities and do not cover whole world regions. As for MOD12, the population figures for the urban areas are not consistent with the UN urban population statistics, while the accuracy level of the land cover map is relatively high in other previous studies.

For this reason, we modify the urban areas indicated by MOD12 in such a way that its urban population figures become equal to the UN urban population statistics for the year 2000. LandScan 2007 and the potential urban areas delineated in Section 4 are also used for this adjustment.

5.1. LandScan 2007 global population database by Oak Ridge National Laboratory (ORNL)

LandScan 2007 is a database of global population distributions in 2007 with resolution of 30 arc seconds that was developed by Oak Ridge National Laboratory (ORNL) to estimate ambient populations at risk. Although it has been updated since 1998, we use the 2007 database because LandScan 2000 is not available at present.

In the LandScan methodology, the probability coefficients of grid cells are calculated based on road proximity, slope, land cover, and nighttime lights. Then population figures from censuses are allocated to each grid cell based on the coefficients at the regional level. The probability coefficients are weighted values of input data and are independent of census data. LandScan represents the mid-year July population estimates for that year, which cannot be used for time-series analysis. Also, the underlying models have not been published, so the assumptions employed by LandScan in distributing population counts to grids are not known [5]. Nevertheless, we adopt this database because there is no other population data set that covers the whole world in high resolution.

5.2. Modification methodology

The procedure for modifying the urban areas depicted in MOD12 is as follows. First, global population distribution maps for 2000 are developed using the population distribution of LandScan 2007 and UN population statistics for 185 countries in an SRES scenario. Next, a grid cell with the highest population density in rural areas is converted to that in urban areas and a population figure in the grid cell is added to urban population figures in MOD12. Then the process is repeated until the urban population figures in MOD12 become equal to the United Nations urban population statistics in 2000 for each country. The resulting land cover map is referred to as MOD12-a. As mentioned, the urban areas in MOD12-a are the composite of the urban areas in MOD12, which are identified by the urban function (man-made structures detected from satellite images) as shown in Figure 2, and the additional areas that are determined by population density. During this process, lower limits for population density are set to eliminate grid cells where population density is significantly low. Toward this end, we rank the urban grid cells in MOD12 in descending order of population density for each country. Then the cumulative value of urban areas is calculated by adding an area of a grid cell in descending order of population density. The lower limit is determined when the cumulative total value reaches 99 percent of the total urban areas in MOD12.

5.3. Results

The urban areas in MOD12-a by UN region are shown in Table 1. The global urban areas comprise 1.12 million km^2, which accounts for 0.8 percent of the world's land area excluding Antarctica. In addition, a comparison of the urban areas in MOD12-a with the original MOD12 land cover map is shown in Table 4. As is shown in this table, 64.1 percent of global urban areas in MOD12-a are located in urban and built-up areas in MOD12, with 18.5 percent in cropland, 8.5 percent in forest or shrublands, and 8.2 percent in grasslands or wetlands.

Table 4. Relationship between the urban areas in the MOD12-a and MOD12 land cover maps

	Aggregated MOD12 Land Cover Class (%)				
Region	Forest and Shrublands	Grasslands and Wetlands	Croplands	Others	Urban and Built-Up
Developing Countries	6.9	11.3	11.3	1.2	69.3
Developed Countries	9.8	5.8	24.1	0.2	60.1
World Total	8.5	8.2	18.5	0.6	64.1

5.4. Comparison of average urban area per person in 2000

Average urban area per person by UN region is shown in Table 5 as calculated from the urban areas in MOD12-a, GRUMP, and the FAO study and the urban population in 2000. Average urban area per person as estimated by Word Bank is also shown in Table 3. The estimates show that estimated per capita urban areas have wide ranges. The global average urban area per person according to GRUMP is 1,228 m^2, which is 6.7 times as large as the World Bank figure (183 m^2). The average urban area per person in developed countries is 1.6 to 2.8 times as large as that in developing countries.

Table 5. Urban population and average urban area per person by UN region

Continent	Region	Urban Population in 2000 (1000 persons)	Average Urban Area per Person (m^2) GRUMP	FAO	MOD12-a
Africa	Eastern Africa	60,500	532	741	349
	Middle Africa	32,660	512	522	242
	Northern Africa	84,630	979	655	268
	Southern Africa	26,800	1,867	794	494
	Western Africa	87,180	460	693	274
Americas	Caribbean	23,300	1,300	872	178
	Central America	92,080	1,333	486	213
	Northern America	239,550	3,701	1,221	814
	South America	276,250	1,358	1,542	311
Asia	Eastern Asia	517,920	574	514	233
	Japan	100,000	1,032	264	523
	South-central Asia	441,380	795	348	226
	South-eastern Asia	195,260	497	430	154
	Western Asia	124,090	1,169	598	324
Europe	Eastern Europe	209,320	1,439	1,041	588
	Northern Europe	77,680	2,017	1,154	717
	Southern Europe	96,300	2,018	513	610
	Western Europe	150,710	1,194	1,495	848
Oceania	Australia and New Zealand	20,640	2,162	2,041	807
	Melanesia	1,620	1,849	1,208	187
	Developing Countries	1,963,890	837	647	249
	Developed Countries	894,200	2,088	1,055	704
	World Total	2,858,090	1,228	774	392

6. Regression analysis of current urban areas

To prepare to estimate future urban expansion, regression analysis was conducted to analyze the urban areas presented in MOD12-a and GRUMP, whose data sets are available for 185 countries with resolution of 30 arc seconds. The FAO and World Bank studies have been excluded because they provide insufficient data for each country.

6.1. Methodology

As shown in equation 1, it is assumed in the present study that the urban area in a certain country can be explained by three explanatory variables: urban population, per capita GDP PPP, and potential urban area per person in 2000. We first take the natural logarithm of both sides in equation 1 and then produce a regression analysis for estimating the elasticity of each variable. Per capita potential urban area is calculated by dividing potential urban area by total population in 2000 as shown in equation 2.

$$UA = A \cdot POPu^{\alpha} \cdot pcGDP^{\beta} \cdot pcBA^{\gamma} \qquad (1)$$

$$pcBA = BA / POP \qquad (2)$$

where *UA* is urban area (km^2), *A* is constant, *POP* is total population (person), *POPu* is urban population (person), *pcGDP* is per capita GDP PPP (2000 Int. $/person), *BA* is potential urban area (buildable area) (km^2), and *pcBA* is per capita potential urban area (m^2/person).

Urban expansion is generally considered to be determined by more varied factors. For example, in the World Bank report, urban areas are explained based on the Alonso model by adding other factors such as transportation costs, agricultural rent, the productivity of export goods and climate conditions [7]. However, in the present analysis, the explanatory variables are narrowed down to population, GDP, and potential urban area. Also, it is known that the globalization of economic activities has affected urban development in developing countries [22]. However, globalization is not taken as an explanatory variable because it displays a high correlation with economic growth in the SRES scenario.

6.2. Results

The results of the regression analysis are shown in Table 6. The model mentioned above appears to perform very well because adjusted R-squared is 0.91 in MOD12-a and 0.88

in GRUMP. All of the parameters are statistically significant at the 1-percent level. The elasticity figures, except those for the urban population data in MOD12-,a, are below 1, which indicates that the growth rates for urban areas decrease with the increase in values for those variables. Meanwhile, urban areas increase linearly with population growth because the elasticity of the urban population in MOD12-a is approximately 1.

Table 6. The results of elasticity estimation

Variable	GRUMP			MOD12-a		
	Coefficient	t-value	Significance Level	Coefficient	t-value	Significance Level
ln (POPu)	0.89	33.8	**	1.04	42.4	**
ln (pcGDP)	0.49	11.5	**	0.31	7.9	**
ln (pcBA)	0.34	8.8	**	0.30	8.3	**
Constant	-12.38	-18.3	**	-13.97	-22.2	**
Number of observations		185			185	
Adjusted R-squared		0.88			0.91	

** Significance at 1 percent level

7. Projection of urban expansion for 185 countries

Given the preliminary analysis above, urban expansion for 185 countries is calculated until 2100 based on the IPCC Special Report on Emissions Scenarios (SRES).

7.1. IIASA’s SRES scenario

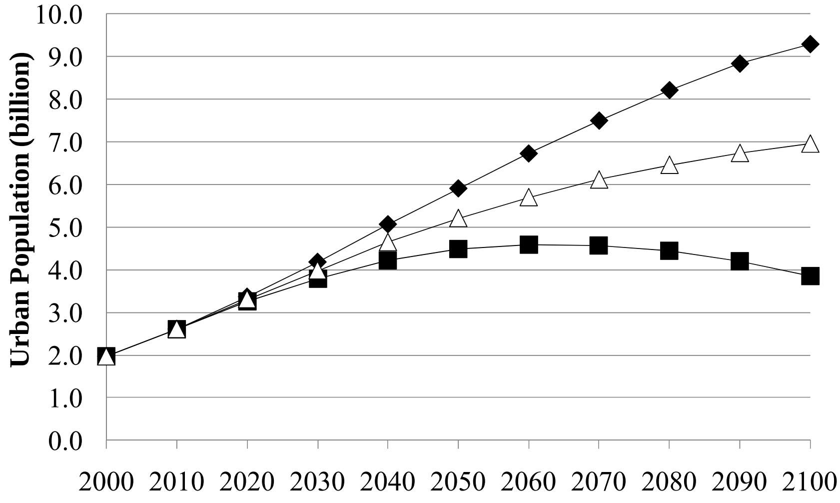
First, SRES scenarios from the International Institute for Applied Systems Analysis (IIASA) are mentioned below [11]. In the scenarios, the population and economic activity (GDP) of 185 countries around the world are quantified for three socioeconomic scenarios (A2, B1, and B2). They are also divided into urban and rural regions for each country and distributed spatially to grid cells at a 0.5 by 0.5 degree resolution. The original A2 scenario is revised to reflect recent changes in perceptions regarding the demographic outlook for world population growth; this revised version is referred to as the A2r scenario.

7.1.1. Urban population

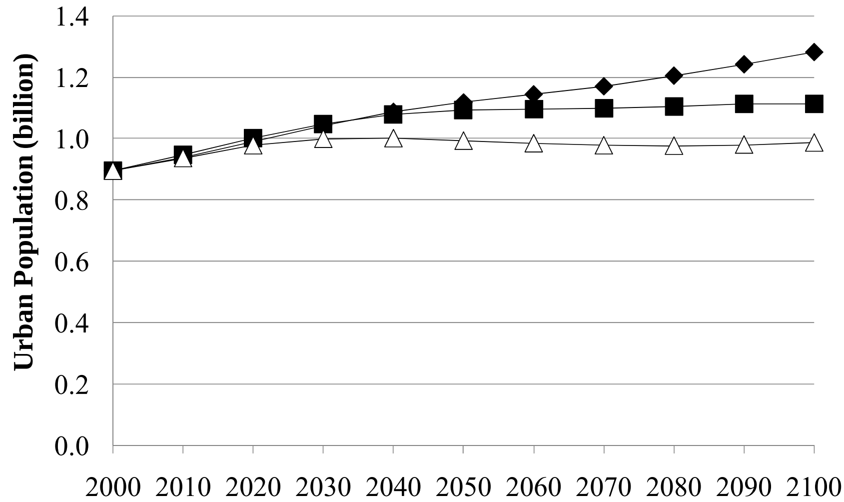
In developing urbanization scenarios, the forecast period is divided into two parts, 1990 to 2030 and 2030 to 2100. For the period 1990 to 2030, the UN projection to the year 2030 is adopted from the 2001 UN urbanization report [10]. After 2030, simple logistic curves are used to determine alternative urbanization trends extending to 2100 based on the following criteria:

1. For all countries with current or UN-projected high levels of urbanization (>80 percent currently or by 2030), a singular urbanization scenario is applied.
2. For countries with low urbanization (<80 percent by 2030), scenario-specific upper bound values are assumed for logistic urbanization growth: that is, 100 percent in the A2r scenario, 60 percent in the B1 scenario, and 80 percent in the B2 scenario.
3. For all those countries where current urbanization rates are already higher than those specified for a given scenario (i.e., B1 and B2), an asymptote that is 10 percent above current levels is assumed. If current urbanization rates were 65 percent, the asymptotic urbanization rates would range between 72, 80, and 100 percent across B1, B2, and A2 scenarios.

Consequently, the global urbanization rates for the three urbanization scenarios cover a range between 70 percent (B1), 76 percent (B2) and 85 percent (A2r) by the year 2100. World urban population levels are projected to reach 4.9 billion (B1), 7.9 billion (B2), and 10.5 billion (A2r), while rural population numbers are predicted to reach 2.0 billion (B1), 2.4 billion (B2), and 1.8 billion (A2r) by 2100. The scenarios for urban population in developing and developed countries are illustrated in Figure 3.



(a) Developing Countries



(b) Developed Countries

Figure 3. Urban population scenarios in SRES (♦ A2r scenario, ■ B1 scenario, Δ B2 scenario)

7.1.2. Per capita GDP

GDP scenarios were originally developed across 11 world regions defined by the IIASA. For the purpose of downscaling these data to national levels, per capita GDP growth is expressed as a function of income levels by region. Then the formula is applied to countries in the region to calculate the GDP growth of each country. To assure that that the summation of national projections is consistent with the original regional GDP, the GDP growth of each country is modified via an optimization algorithm that is subject to regional GDP. These GDP values are given in 1990US$ at market exchange rates. In the present analysis, they are converted to purchasing power parity-based GDP in Int.$2000 using the World Bank data sets [23].

Scenarios of purchasing power parity-based GDP per capita are shown in Figure 4. As is shown in the figure, GDP per capita results in narrow ranges among the three scenarios in the developed countries, while in the developing countries, the scenarios differ markedly: from 38 thousand dollars (A2r) to 160 thousand dollars (B1) in 2100.

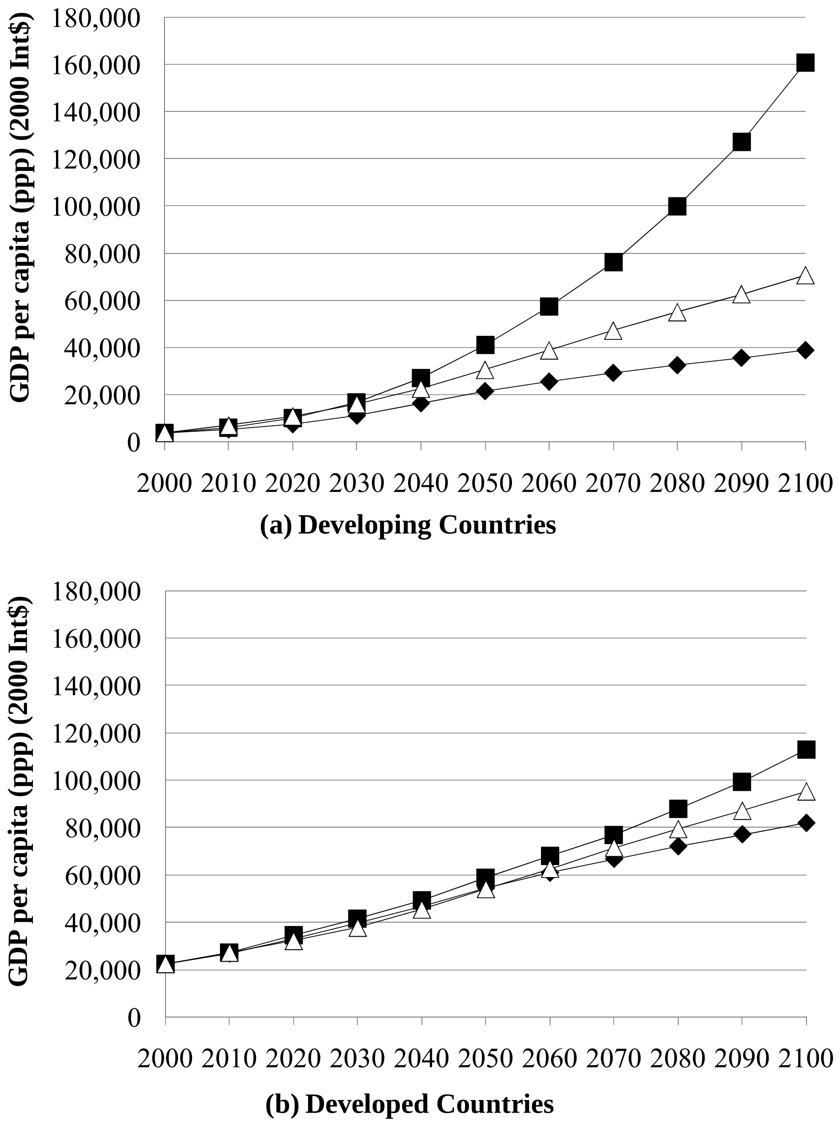


Figure 4. Per capita GDP scenarios in SRES (♦ A2r scenario, ■ B1 scenario, Δ B2 scenario)

7.1.3. Per capita potential urban area

Per capita potential urban area scenarios are developed by dividing each country's potential urban area in 2000 by its total population in the future (Figure 5). As is shown in the figure, future per capita potential urban area does not show significant changes from 2000 levels in the developed countries, while in the developing countries, it decreases to about half of the 2000 level by 2100 in the A2r and B2 scenarios. The reduction of per capita potential urban area causes the decrease in projected future urban areas.

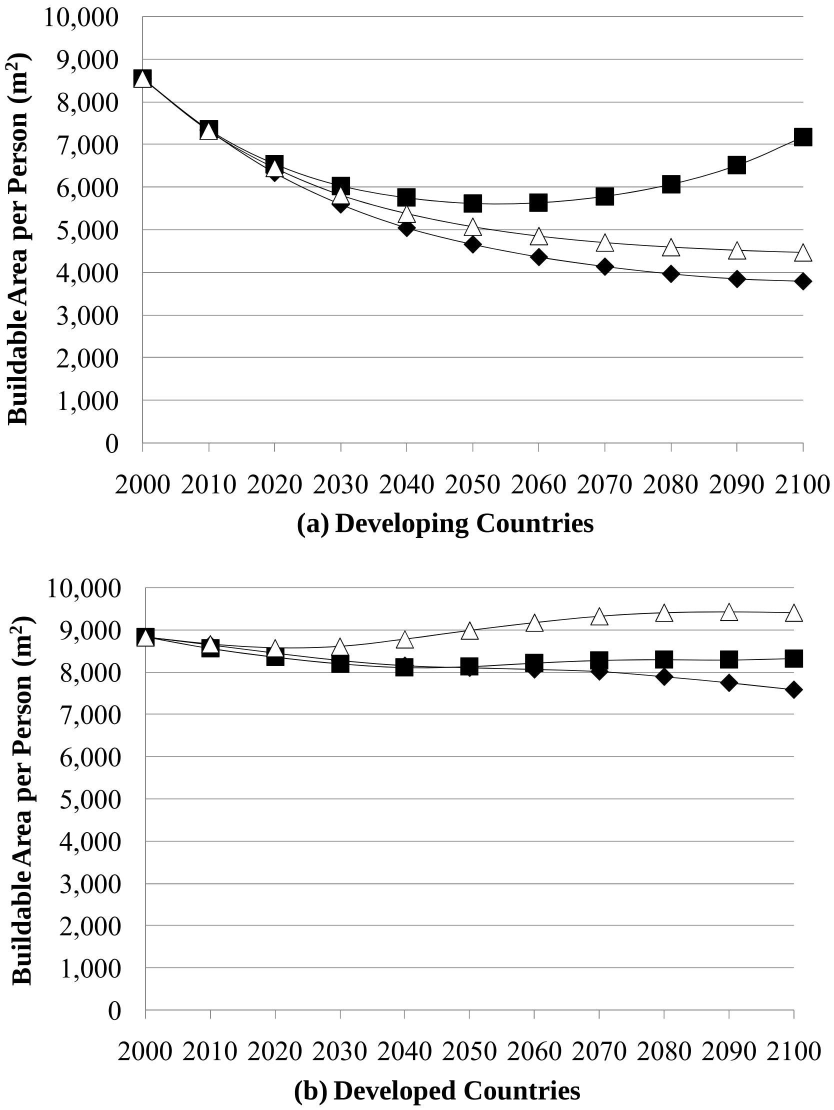


Figure 5. Per capita potential urban area scenarios in SRES (♦ A2r scenario, ■ B1 scenario, Δ B2 scenario)

7.1.4. Factors of urban population increases

There are two factors of urban population increase: natural increase and rural-urban migration. In the IIASA scenario, it is explained that urban population increases due to rural-urban migration, which is caused by the income disparity between urban and rural areas. It is assumed that the higher a country's per capita GDP growth is in a particular scenario, the faster rural–urban income disparities will converge, with asymptotic convergence levels ranging between 0.7 (A2r) and 1 (B1) across the three scenarios. For the B1 scenario, in which rural-urban income differences are gradually eliminated, the urbanization rate remains low due to a decrease in migration. In contrast, for the A2r scenario, in which rural-urban income differences are slowly eliminated, the urbanization rate increases because rural-urban migration is maintained at a high level.

Meanwhile, the United Nations Population Fund (UNFPA) reports that the dominant factor in urban population increase today is not migration but natural increase. The latest comprehensive research effort to separate natural increase from other components of urban growth puts the contribution of natural increase at about 60 percent in the median country [24]. However, natural increase in urban areas is not illustrated in the IIASA scenario, wherein the urban population is calculated by multiplying the total population in a country by its urbanization rate.

7.2. Projection of future urban expansion

Next, future urban expansion for 185 countries is projected using the elasticities estimated in Section 6. In addition, figures for future urban expansion in the case of constant per capita urban area are calculated to create points of reference. In both cases, future urban expansion is subject to potential urban areas as estimated in Section 4.

7.2.1. Constant per capita urban area case

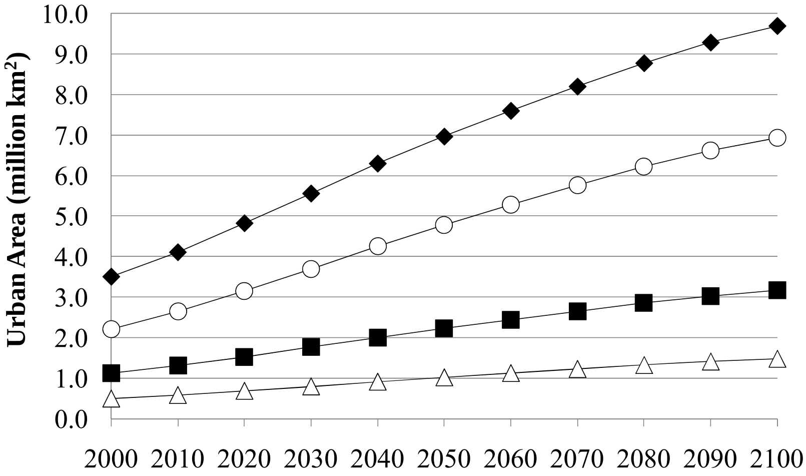
Methodology

In this case, future urban areas are calculated by multiplying future urban population figures by per capita urban areas at 2000 levels from MOD12-a, GRUMP, the FAO and the World Bank. As for per capita urban areas, the national average for each country is used in MOD12-a and GRUMP, while in the FAO and World Bank information, regional averages are used instead of national averages [25]. Future urban expansion is subject to the potential urban areas for each country as estimated in Section 4.

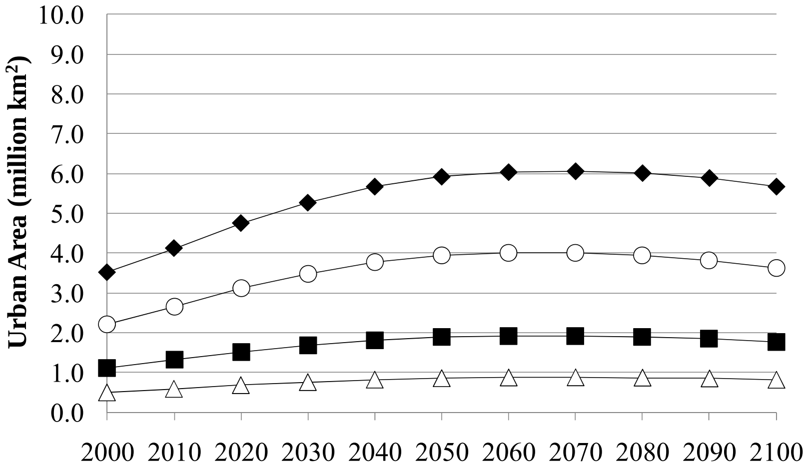
Results

The results of the calculations of global urban areas are shown in Figure 6. Comparing the three scenarios, we find that the maximum values of global urban areas are 3.16 million km^2 in 2100 (A2r), 1.92 million km^2 in 2070 (B1), and 2.38 million km^2 in 2100 (B2) in the case of MOD12-a, which are 2.8 times as large as the urban areas at 2000 levels in the A2r scenario, 1.7 times as large in the B1 scenario, and 2.1 times as large in the B2 scenario.

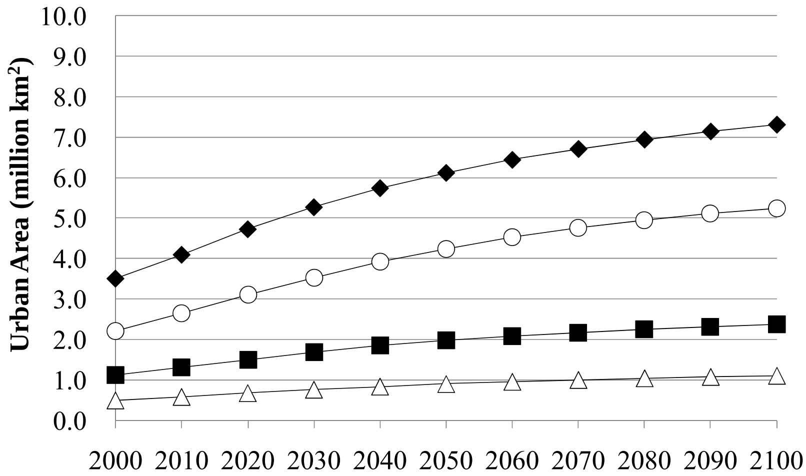
On the other hand, across the previous works, it is shown that the difference in estimated urban areas in 2000 has a significant effect on future urban expansion. For example, in the case of the B2 scenario, global urban areas in 2000 constitute 1.12 million km^2 in MOD12-a, 3.51 million km^2 in GRUMP, and 0.5 million km^2 in FAO, while they will expand to 2.38 million km^2, 7.31 million km^2, and 1.11 million km^2, respectively, in 2100.



(a) A2r Scenario



(b) B1 Scenario



(c) B2 Scenario

Figure 6. Future global urban areas in the case of constant per capita urban area (■ MOD12-a, ♦ GRUMP, ○ FAO, Δ World Bank)

7.2.2. Estimation by regression equation

Methodology

In the calculations using the regression equation, per capita GDP is fixed at 35,000 dollars when it is beyond this income level in each scenario, which is the maximum value of per capita GDP in 2000 in 185 countries. The resultant indication is that urban expansion due to economic growth is saturated when per capita GDP goes beyond that level. As shown in equation 3, future urban expansion for a country ($UE_{\mathrm{i,t}}$) is calculated by adding its urban area in 2000 ($UE_{\mathrm{i,2000}}$) to the difference between future urban area and urban area in 2000 as calculated from equation 4.

$$UE_{\mathrm{i,t}} = UE_{\mathrm{i,2000}} + (UA_{\mathrm{i,t}} - UA_{\mathrm{i,2000}}) \qquad (3)$$

$$UA_{\mathrm{i,t}} = A \cdot POPu_{\mathrm{i,t}}^{\ \alpha} \cdot pcGDP_{\mathrm{i,t}}^{\ \beta} \cdot pcBA_{\mathrm{i,t}}^{\ \gamma} \qquad (4)$$

where i is a country, and t is a year.

Results

Consequently, the maximum values of global urban areas are 4.82 million km^2 in 2100 (A2r), 3.17 million km^2 in 2070 (B1), and 4.13 million km^2 in 2100 (B2) based on MOD12-a; these figures are 4.3 times as large as those for the urban areas at 2000 levels in the A2r scenario, 2.8 times as large in the B1 scenario, and 3.7 times as large in the B2 scenario (Figure 7).

Meanwhile, comparing MOD12-a with GRUMP, we also show that the difference between the urban areas estimated for 2000 has a significant effect on future urban expansion. For example, in the case of the B2 scenario, global urban areas in 2000 are 1.12 million km^2 based on MOD12-a and 3.51 million km^2 based on GRUMP, while by 2100, they will expand to 4.13 million km^2 and 11.94 million km^2, respectively. The gaps between the two will grow over time.

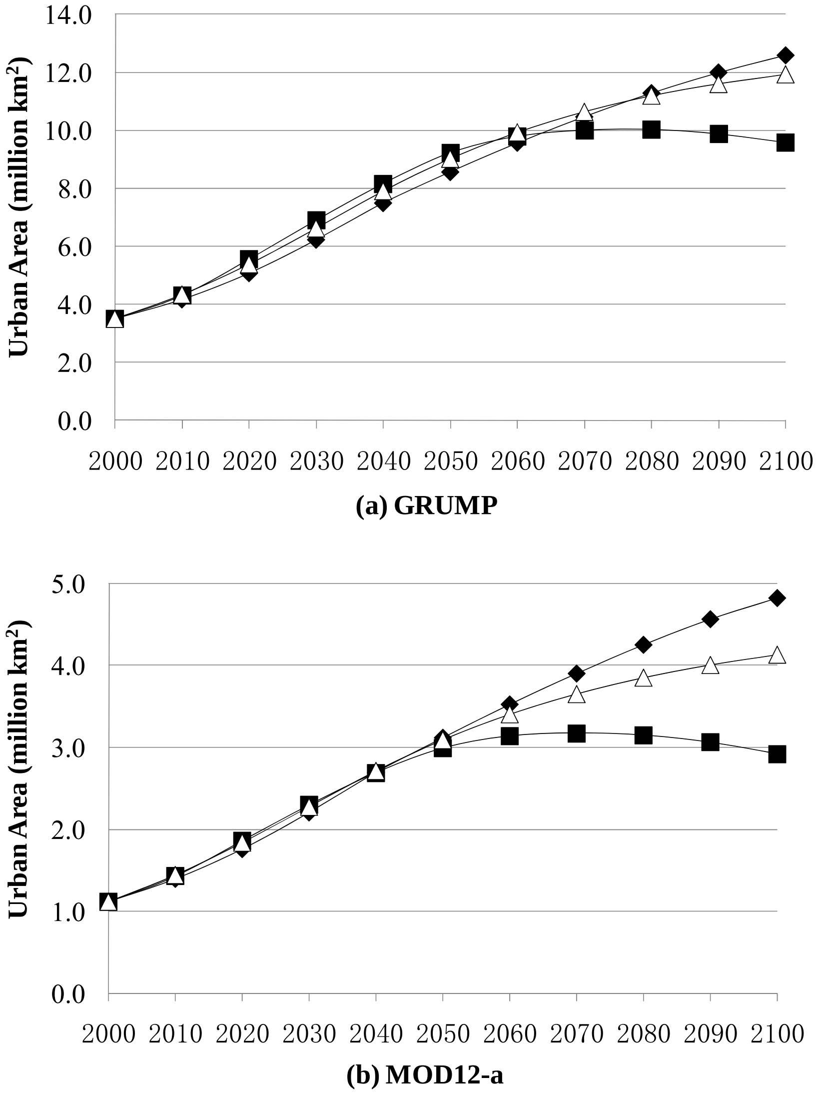


Figure 7. Future global urban areas using a regression equation
(♦ A2r scenario, ■ B1 scenario, Δ B2 scenario)

8. Reduction of existing cropland due to urban expansion

In this section, we first consider how urban areas expand spatially. Then we calculate the loss of existing cropland due to urbanization.

8.1. Methodology

Using urbanization potential is one method of estimating spatial urban expansion. Using the method, a land area is divided into grid cells first, after which the urbanization potential of each grid is estimated. Then, grid cells in rural areas are converted to those of urban areas in descending order of grid urbanization potential in such a way that the area of the total urban grid cells becomes equal to the estimated urban expansion. Urbanization potential in a certain grid is dependent on both its suitability for urban development and the effect of neighboring grids. For example, land use change in the Mekong Basin is simulated using a model based on cellular automata developed by the Geographical Survey Institute [26]. However, urbanization potential is determined by various factors that relate to geographical and socio-economic conditions. It is very difficult to estimate urbanization potential in the present analysis because it is necessary to prepare for all of these various factors for a very extended period globally.

On the other hand, future changes in the spatial urban population distribution have been estimated using potential population figures in the IIASA report [11]. First, the population potential of each grid is calculated from population distribution with resolution of 7.5 arc minutes. Then, future changes in the total urban population in a country are allocated to each grid in proportion to its population potential. Population potential is based on a gravity model that is used to explain inter-region interaction, as in population migration [27]. Therefore, in the estimation of future urban population distribution, rural-urban migration, which is one of the main factors of urban population increase, can be explained according to population potential. However, it is not impossible to illustrate the mechanisms of natural increase by population potential, which is the most important factor of urban population increase today, as mentioned above.

Because of the limitations of the existing methodologies, it is simply assumed in the present analysis that the urbanization potential of a grid in rural area is proportional to its population density in 2000. That is, grid cells that are located in both rural and potential urban areas are converted to urban areas in descending order of 2000 population density figures such that the area of the total urban grid cells becomes equal to the urban expansion estimated using the regression equation. This assumption indicates that the urban area is determined by population, which is one of characteristics that define urbanity as noted in Figure 2, and that relationships between urbanization potential figures for the different grids are constant throughout the estimation period. The current population density of a certain grid represents not only its geographical conditions, such as water availability and a climate suitable for inhabitation, but also the accumulation of infrastructure and economic activity levels at present. However, this assumption does not consider factors that affect urbanization potential in the long run such as climate change. It does not also treat discontinuous development, as in the case of Brasilia, which has been constructed in an undeveloped region.

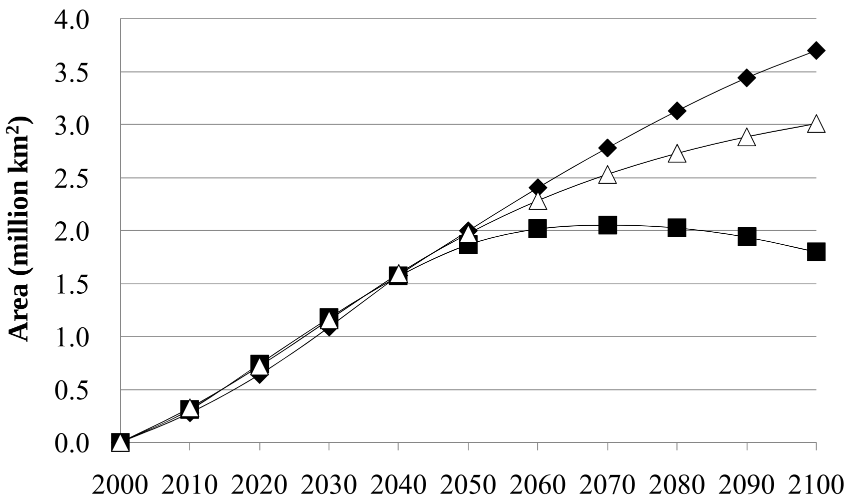
8.2. Results

Cropland losses due to diversion to urban areas as noted in MOD12-a are shown in Table 7. Based on the land cover classification used in MOD12 (Table 2), global cropland areas in 2000 compose 15.9 million km^2 and consist of (12) croplands and (14) a cropland/natural vegetation mosaic. Global cropland reductions due to diversion to urban areas will be 1.01 million km^2 (6.4 percent of total croplands in 2000) under the A2r scenario, 0.89 million km^2 (5.6 percent) under the B1 scenario, and 0.98 million km^2 (6.1 percent) under the B2 scenario in 2050. Furthermore, they will be 1.8 million km^2 (11.3 percent) under the A2r scenario, 1.0 million km^2 (6.3 percent) under the B1 scenario, and 1.39 million km^2 (8.8 percent) under the B2 scenario in 2100. In addition, global cropland losses account for approximately half of global urban expansion as shown in Figure 8. Regionally, cropland reduction rates in developing countries are much higher than those in developed countries. They will be 19.6 percent in the A2r scenario, 10.3 percent in the B1 scenario, and 15.4 percent in the B2 scenario in 2100. In particular, reduction rates are very high in Asia.

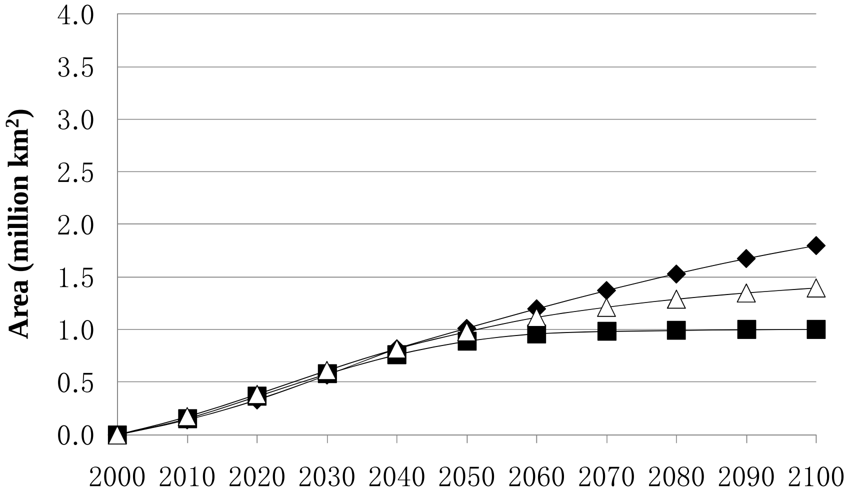
In the phase in which the urban population is projected to decrease, which will occur in the second half of this century in the B1 scenario, it is reported that unnecessary buildings and parking will be removed and converted to green spaces or employed for other land use purposes [28]. However, the present analysis assumes that they are not diverted to cropland again.

Table 7. Cropland area in 2000 and future decrease ratios by UN region (MOD12-a)

Continent	Region	Cropland Area in 2000 (1000 km^2)	Decrease Ratios in Cropland Area from their 2000 levels (%). A2r Scenario				B1 Scenario				B2 Scenario			
			2020	2050	2070	2100	2020	2050	2070	2100	2020	2050	2070	2100
Africa	Eastern Africa	292.5	1.1	6.0	11.7	17.9	1.5	9.6	12.9	13.9	1.4	8.3	15.7	22.6
	Middle Africa	38.4	1.7	6.5	9.6	12.4	2.4	8.0	9.8	10.1	2.0	7.5	10.7	13.7
	Northern Africa	192.1	4.4	15.0	21.5	26.8	4.8	15.6	17.5	17.9	3.6	14.0	18.7	20.2
	Southern Africa	58.1	1.2	3.6	5.4	7.5	1.6	3.0	3.0	3.0	1.4	3.4	3.8	3.9
	Western Africa	152.0	1.3	5.3	8.8	12.8	1.5	6.9	9.3	9.6	1.5	6.7	11.0	15.0
Americas	Caribbean	80.3	1.8	4.8	6.6	9.1	2.7	4.6	5.0	5.0	2.0	4.7	5.6	6.2
	Central America	241.1	2.5	8.3	11.4	14.3	4.3	7.0	7.4	7.5	2.6	7.5	9.0	9.7
	Northern America	2,730.4	0.6	1.3	1.6	2.0	0.5	1.1	1.4	1.8	0.5	0.9	1.0	1.1
	South America	1,385.5	1.2	3.6	4.7	5.5	2.0	3.3	3.4	3.4	1.3	3.6	3.9	4.2
Asia	Eastern Asia	2,083.4	6.5	18.5	22.3	27.5	6.7	12.3	12.3	12.3	8.0	16.5	18.2	19.6
	Japan	33.4	5.7	6.7	7.3	8.9	6.0	6.5	6.5	6.5	3.9	5.0	5.0	5.0
	South-central Asia	2,776.1	2.4	9.2	15.1	22.0	2.4	9.4	11.5	11.6	2.5	10.0	14.5	18.2
	South-eastern Asia	682.2	4.1	12.9	17.7	22.8	4.4	12.3	13.0	13.0	6.0	13.9	16.2	18.0
	Western Asia	362.3	2.3	7.3	9.8	11.3	2.7	7.1	7.8	7.9	3.1	7.5	8.5	9.0
Europe	Eastern Europe	3,102.8	0.7	1.8	1.8	2.0	0.8	1.8	1.8	1.8	0.6	1.3	1.3	1.3
	Northern Europe	282.3	1.4	2.7	3.3	4.4	1.6	2.7	3.0	3.3	1.5	2.3	2.6	2.8
	Southern Europe	488.4	1.1	2.0	2.2	2.5	1.3	2.0	2.0	2.0	1.2	1.7	1.8	1.8
	Western Europe	468.0	1.7	2.8	3.3	4.6	1.9	2.7	2.8	3.1	1.7	2.3	2.4	2.7
Oceania	Australia and New Zealand	456.4	0.2	0.4	0.5	0.6	0.2	0.4	0.4	0.4	0.2	0.3	0.3	0.4
	Melanesia	0.6	1.5	5.0	8.6	12.2	1.8	5.8	8.6	9.5	2.2	7.1	9.8	12.2
	Developing Countries	8,344.6	3.3	10.6	14.8	19.6	3.6	9.2	10.2	10.3	4.0	10.6	13.3	15.4
	Developed Countries	7,561.8	0.7	1.7	1.9	2.2	0.8	1.6	1.7	1.9	0.7	1.2	1.3	1.4
	World Total	15,906.3	2.1	6.4	8.6	11.3	2.3	5.6	6.2	6.3	2.4	6.1	7.6	8.8



(a) Additional Urban Area from the 2000 levels



(b) Cropland diverted to Urban Area

Figure 8. Comparison of additional urban areas with global cropland losses (MOD12-a) (♦ A2r scenario, ■ B1 scenario, Δ B2 scenario)

9. Reduction of potential crop production from existing cropland

Finally, the reduction in potential crop production for each country is estimated based on the cropland losses in the previous section and spatial distribution of potential crop yields.

9.1. Methodology

The data set for the IIASA GAEZ analysis is adopted to determine the spatial distribution of potential crop yield in the world. In the GAEZ analysis, maximum crop yields are estimated under average climate conditions for the period from 1961 to 1990 with resolution of 5 arc minutes where the best available technologies and multiple cropping are introduced. The global potential crop production in 2000 from the croplands indicated in MOD12-a is estimated at 7.05 billion tons using the GAEZ data set, which corresponds to approximately 3.4 times as much as FAOSTAT's global cereal production in 2000 (2.06 billion tons) [29].

9.2. Results

Future reduction ratios of potential crop production by UN region are shown in Table 8. Consequently, it seems that global potential crop production will decrease by 8.5 percent in the A2r scenario, 7.4 percent in the B1 scenario, and 8.3 percent in the B2 scenario in 2050 compared to 2000 levels. By 2100, they will decrease from 2000 levels by 15.8 percent in the A2r scenario, 8.3 percent in the B1 scenario, and 12.1 percent in the B2 scenario. Regionally, reduction ratios are especially high in the developing countries. Their potential crop production will decrease from 2000 levels by 25.5 percent in the A2r scenario, 12.7 percent in the B1 scenario, and 19.9 percent in the B2 scenario in 2100.

Table 8. Potential production in 2000 and future decrease ratios by UN region (MOD12-a)

Continent	Region	Potential Production in 2000 (1000 ton)	Decrease Ratios in Potential Production from their 2000 levels (%). A2r Scenario				B1 Scenario				B2 Scenario			
			2020	2050	2070	2100	2020	2050	2070	2100	2020	2050	2070	2100
Africa	Eastern Africa	86,929	1.1	5.6	10.9	16.6	1.4	8.9	12.1	12.9	1.3	7.8	14.6	20.8
	Middle Africa	17,493	0.8	4.0	6.5	9.2	1.1	5.6	6.6	6.8	1.0	5.1	7.3	9.9
	Northern Africa	93,136	2.5	9.1	14.2	17.1	2.8	9.5	11.2	11.8	2.1	8.4	12.5	13.6
	Southern Africa	4,810	1.4	4.3	6.3	8.7	1.9	3.6	3.6	3.6	1.7	4.1	4.5	4.6
	Western Africa	82,787	1.3	5.2	8.7	12.9	1.6	6.9	9.4	9.7	1.5	6.8	11.4	15.6
Americas	Caribbean	41,764	1.7	4.3	5.8	7.9	2.5	4.2	4.5	4.5	1.9	4.3	4.9	5.2
	Central America	96,067	2.5	8.0	11.3	14.6	4.2	6.6	7.0	7.1	2.6	7.2	8.6	9.4
	Northern America	1,335,133	0.8	1.8	2.3	2.9	0.8	1.6	2.0	2.6	0.8	1.3	1.4	1.6
	South America	740,585	1.2	3.7	4.8	5.7	2.0	3.3	3.4	3.4	1.3	3.6	4.0	4.3
Asia	Eastern Asia	791,795	9.5	28.5	34.4	42.5	9.8	18.4	18.4	18.4	11.8	25.4	28.0	30.1
	Japan	11,015	7.3	8.4	9.1	10.8	7.7	8.2	8.2	8.2	5.0	6.4	6.4	6.4
	South-central Asia	1,593,826	3.1	11.8	19.9	29.4	3.2	12.2	14.5	14.5	3.4	13.1	19.0	24.0
	South-eastern Asia	414,601	4.6	14.5	20.0	25.8	4.8	13.9	14.7	14.8	6.6	15.6	18.4	20.6
	Western Asia	60,183	3.5	10.4	13.7	16.1	4.0	10.1	11.2	11.3	4.5	10.6	12.1	12.7
Europe	Eastern Europe	1,069,682	0.8	2.1	2.2	2.4	0.9	2.1	2.1	2.1	0.7	1.6	1.6	1.6
	Northern Europe	126,977	1.7	3.3	4.0	5.4	1.9	3.3	3.7	4.1	1.8	2.8	3.1	3.4
	Southern Europe	108,825	1.9	3.0	3.2	3.7	2.2	3.0	3.0	3.0	1.9	2.7	2.7	2.7
	Western Europe	217,404	1.7	2.9	3.5	4.9	2.0	2.9	3.0	3.3	1.8	2.4	2.5	2.8
Oceania	Australia and New Zealand	156,699	0.2	0.5	0.5	0.6	0.3	0.4	0.4	0.4	0.2	0.3	0.4	0.4
	Melanesia	72	1.0	3.1	7.0	10.4	1.4	4.2	6.9	7.8	1.4	5.3	7.9	10.8
	Developing Countries	4,024,050	4.0	13.3	18.9	25.5	4.4	11.4	12.6	12.7	4.8	13.3	17.0	19.9
	Developed Countries	3,025,735	1.0	2.1	2.4	2.9	1.0	2.0	2.2	2.5	0.9	1.5	1.6	1.7
	World Total	7,049,786	2.7	8.5	11.8	15.8	2.9	7.4	8.1	8.3	3.1	8.3	10.4	12.1

On the other hand, per capita potential crop production will decrease from 2000 levels due to population growth even if cropland areas do not decrease due to urban expansion. However, global average per capita potential crop production will decrease by an additional 2.1 to 7.1 percent due to urban expansion throughout the projection periods (Table 9).

Table 9. Contribution of urban expansion to the reduction of per capita potential crop production (MOD12-a)

Region	Potential Production per Person in 2000 (ton)	Decrease Ratios in Potential Production per Person from their 2000 levels (%).											
		A2r Scenario				B1 Scenario				B2 Scenario			
		2020	2050	2070	2100	2020	2050	2070	2100	2020	2050	2070	2100
(a) Fixed Urban Area													
Developing Countries	0.83	26.0	45.6	51.7	55.8	23.5	34.4	32.4	16.0	24.5	40.6	45.0	47.7
Developed Countries	2.55	4.3	8.2	9.2	14.0	5.3	7.8	6.2	5.7	2.9	-1.8	-5.7	-6.6
World Total	1.16	22.5	40.9	46.8	51.1	20.5	30.4	28.5	14.2	21.1	35.4	39.3	41.9
(b) Urban Expansion													
Developing Countries	0.83	28.9	52.9	60.8	67.0	26.8	41.9	40.9	26.7	28.2	48.6	54.3	58.1
Developed Countries	2.55	5.2	10.1	11.4	16.5	6.3	9.6	8.2	8.0	3.8	-0.3	-3.9	-4.8
World Total	1.16	24.6	45.9	53.1	58.8	22.8	35.5	34.3	21.3	23.6	40.7	45.6	48.9

The reduction ratios of potential national crop production are also shown in Table 10, where the top 30 countries for potential crop production are arranged in descending order. Total potential production among the top 30 countries accounts for 91 percent of global potential production in 2000. Consequently, it has been shown that reduction rates will be remarkably high in Asian developing countries: namely, Pakistan, Bangladesh, Indonesia, the Philippines, China, Vietnam, Cambodia, India, and Myanmar. As for Pakistan, this is because the urban population in 2100 will reach 3.8 (B1) to 8.0 times (A2r) as much as that in 2000.

Table 10. Potential crop production decrease ratios by country (MOD12-a)

Country	Potential Production in 2000 (1000 ton)	Decrease Ratios in Potential Production from their 2000 levels (%). A2r Scenario				B1 Scenario				B2 Scenario			
		2020	2050	2070	2100	2020	2050	2070	2100	2020	2050	2070	2100
India	1,354,057	2.9	10.5	17.6	26.0	2.9	10.6	12.2	12.2	3.1	11.6	16.5	20.5
United States of America	1,201,802	0.8	1.9	2.4	3.0	0.8	1.7	2.1	2.7	0.8	1.3	1.5	1.7
China	774,291	9.5	28.7	34.6	42.8	9.7	18.4	18.4	18.4	11.8	25.5	28.2	30.3
Russian Federation	507,000	0.7	1.9	1.9	2.1	0.8	1.9	1.9	1.9	0.5	1.3	1.3	1.3
Argentina	330,675	0.8	2.9	3.6	4.4	1.6	2.3	2.3	2.3	1.0	2.6	2.9	3.2
Brazil	320,987	1.5	4.3	5.6	6.5	2.4	4.1	4.1	4.1	1.4	4.4	4.7	5.0
Ukraine	219,170	0.4	2.1	2.1	2.3	0.4	1.9	1.9	1.9	0.4	1.4	1.4	1.4
Thailand	167,756	1.3	4.2	6.2	9.5	1.3	4.1	4.6	4.6	2.3	4.5	5.8	7.6
Australia	154,433	0.2	0.4	0.5	0.6	0.3	0.4	0.4	0.4	0.2	0.3	0.4	0.4
Canada	133,331	0.7	1.4	1.5	1.7	0.7	1.4	1.6	2.0	0.6	0.9	0.9	0.9
France	120,102	1.4	2.6	3.2	4.2	1.5	2.3	2.3	2.4	1.4	2.2	2.4	2.6
Poland	116,701	1.9	2.9	3.1	3.5	2.2	3.1	3.1	3.1	1.6	2.5	2.5	2.5
Bangladesh	92,334	5.3	24.3	42.2	62.7	6.5	28.4	32.0	32.0	6.3	27.9	42.5	56.0
Myanmar	77,534	3.6	12.5	18.3	22.8	3.5	12.2	13.2	13.2	5.0	14.7	17.7	19.6
Sudan	75,177	0.4	2.6	5.8	6.5	0.5	2.9	4.1	4.8	0.4	2.3	5.1	5.8
Belarus	74,582	0.5	1.7	2.1	2.2	0.6	1.9	2.0	2.0	0.6	1.3	1.4	1.4
Germany	72,525	2.0	3.2	3.6	5.4	2.4	3.6	3.7	4.3	2.2	2.5	2.5	2.9
Mexico	69,849	2.6	8.1	10.8	12.8	4.7	6.2	6.3	6.3	2.7	7.1	7.7	8.2
Pakistan	65,345	5.3	24.8	42.6	59.5	5.5	26.7	38.5	38.7	5.7	29.0	46.0	58.4
United Kingdom	62,394	2.8	5.2	6.5	8.6	3.1	5.2	6.0	6.7	3.0	4.5	5.0	5.6
Romania	57,951	1.1	2.9	3.0	3.6	1.3	3.0	3.0	3.0	0.8	2.5	2.5	2.5
Indonesia	46,428	16.6	43.8	51.5	57.6	16.0	41.3	41.3	41.3	20.3	45.6	48.9	49.8
Viet Nam	45,321	5.6	20.0	28.6	39.6	7.3	16.0	16.8	16.8	8.5	19.5	24.0	28.2
Italy	41,801	1.8	2.1	2.1	2.3	2.3	2.5	2.5	2.5	2.1	2.1	2.1	2.1
Hungary	41,572	1.3	1.7	1.8	2.2	1.5	1.8	1.8	1.8	1.2	1.5	1.5	1.5
Cuba	36,283	1.2	2.7	3.6	5.0	1.9	2.9	2.9	2.9	1.5	2.9	2.9	2.9
Cambodia	36,212	2.4	10.6	19.7	29.9	2.7	10.1	12.6	13.1	3.2	12.0	16.7	21.5
Uruguay	34,671	0.7	2.2	2.7	3.2	1.5	1.9	1.9	1.9	0.9	2.1	2.3	2.5
Turkey	30,699	3.7	10.1	12.5	13.4	4.4	9.5	9.7	9.7	5.7	10.6	11.2	11.3
Philippines	28,847	7.7	28.8	39.9	48.7	8.5	31.3	32.7	32.7	14.0	32.6	36.6	38.8

10. Conclusions

In the present analysis, the impact of urban expansion on cropland and potential crop production is estimated assuming that developing countries will follow the same developmental path as developed countries in terms of population and economic growth. As a result, it has been shown that there are high levels of uncertainty in estimating future urban areas because current urban areas are estimated quite differently in the relevant previous studies.

This study estimates current global urban areas to be approximately half of those indicated in the FAOs' analysis. Nevertheless, it has been shown based on this analysis that future reductions in potential crop production will be especially high under all scenarios, especially in developing Asian countries. For example, although it is estimated that the global average ratios of potential crop production due to urbanization will range from 7.4 percent to 8.5 percent in 2050, it seems that they will be higher in the Asian developing countries: 41.3 percent in Indonesia, 31.3 percent in the Philippines, and 28.4 percent in Bangladesh under the B1 scenario, in which population growth is smaller than in the other two socioeconomic scenarios. In addition, considering future decreases in per capita potential crop production due to population growth, it is shown that research investments in improving crop yields and the construction of agricultural infrastructure will become much more important in developing regions.

Although the median figure for the world population that can be supported by current cropland areas is estimated to be approximately 8 billion people in our previous study [30], this figure must be revised down in consideration of future urban expansion. This revision also indicates that population stabilization in developing countries is an urgent issue.

Top-down analyses using macro-economic models have been conducted to achieve long-term projections regarding global land use changes in climate change research. However, the estimations regarding future cropland areas are quite different depending on the models used, even if they are based on the same socio-economic scenarios [31]. The present study allows us to validate the long-term estimations of land use change.

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