Global urbanization benefits food security and nature restoration

Sitong Wang
Zhejiang University  https://orcid.org/0000-0001-8680-4656

Ouping Deng
College of Resources, Sichuan Agricultural University, Chengdu, China.

Stefan Reis
UK Centre for Ecology & Hydrology  https://orcid.org/0000-0003-2428-8320

Yong-Guan Zhu
Institute of Urban Environment, Chinese Academy of Sciences

Jianming Xu
Zhejiang University  https://orcid.org/0000-0002-2954-9764

Baojing Gu  (bjgu@zju.edu.cn)
Zhejiang University  https://orcid.org/0000-0003-3986-3519

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Abstract

Urbanization has been considered as an antagonist to food security and nature restoration due to land-taking by urban expansion. However, if urbanization was undertaken with a focus on integrated urban–rural development, it could in face release land areas globally. Here show that domestic rural-to-urban migration with urbanization can support a global population with 2 billion more people, while requiring 49 million hectares of less built-up lands due to higher population density in urban relative to rural areas, over the period from 2020 to 2050. If no urbanization would occur, currently predicted growth trends in global population would require an additional 46 million hectares of lands. If cross-countries rural-to-urban migration is supported, land release could be increased up to 67 million hectares. This amount could satisfy 51% of global cropland demand in 2050, and as an additional benefit, reduce cropland fragmentation. If the land areas released were set aside for nature restoration, 4,488 more species could be protected. As a further co-benefit, additional carbon sequestration of 15 billion tonnes could be achieved over the period from 2020 to 2050. Policies to promote cross-countries rural-to-urban migration and management of released lands would help to benefits food security and natural restoration.

Introduction

As a key driver of land use change, urbanization and its impacts on croplands and natural land have been considered a threat to food security and nature restoration\(^1\)\(^-\)\(^4\). Previous studies indicate that between 2000 and 2030, urban expansion will have caused a loss of cropland area between 1.8 and 2.4%, leading to a 3-4% decline in crop production at a global scale\(^1\). These findings have been sufficient to establish urbanization as a major global threat to food production as a widely accepted concept by scholars and the public. As a consequence, government policies regulating the occupation of cropland by urban expansion have been limiting urbanization\(^5\)\(^,\)\(^6\). In addition, the impact of urban expansion on natural lands has resulted in concerns on biodiversity conservation\(^7\)\(^-\)\(^9\), and the intermediate loss of natural lands due to the cropland displacement is greater than the direct loss of natural land occupied by urban expansion\(^3\). Between 1992 and 2015, urban expansion globally caused a direct loss of natural lands of around 7.9 million hectares (Mha), while cropland displacement caused indirect losses of between 24.8 and 49.8 Mha\(^3\).

Previous studies were based on the prevailing paradigm that urbanization inevitably leads to a net-loss of croplands and natural lands. We demonstrate here that without an integrated consideration of urban-rural integration, the true impact of urbanization cannot be adequately assessed at global scale. Our previous study has found that urbanization could, in fact, release land areas for crop production, because rural-to-urban migration free up a larger proportion of built-up land in rural areas, compared to the newly urbanized land occupation in urban areas in China \(^10\). For the period from 2020 to 2050, we assume that overall the degree of urbanization would increase from 56% to 68%, globally, in line with projections of the United Nations, while the global urban population would increase by 2.3 billion over the same period. Over the same period, global rural population would decrease by 320 million\(^11\), hence offering opportunities for
the release of land in rural areas. However, global data is scarce as to what extent the land released in rural areas would meet the requirements for land occupation as new urban areas.

According to the Food and Agriculture Organization of the United Nations (FAO), global crop food production will have to increase by 37% to meet the increasing demand of a growing world population by 2050. Based on traditional assessments, the relative contribution of cropland area expansion would be 24%, i.e., cropland area would need to increase by 145 Mha globally. We analyzed data for 219 countries and their specific projected urbanization processes for the period between 2020 and 2050 with the aim to address the following vital questions: (1) How would global land use change – in the context of increasing urbanization - if integrated urban–rural development would become the prevalent approach? (2) To what extent would land use change affect future global food production and create opportunities for fast-tracking nature restoration? (3) What is the role of cross-countries rural-to-urban migration in safeguarding food security and improving nature restoration in a global urbanization context?

**Results And Discussion**

**Population and land use change**

Based on UN projections, we divided 219 global countries into 3 groups, determined by the projected net change of urban and rural populations over the period from 2020 to 2050. ‘Group I’ countries have both increase in urban and rural population, mainly from Sub-Saharan Africa and Central and West Asia. ‘Group II’ represent countries that urban population would increase while rural population would decrease, mainly including China, Russia, United States, India, France, Germany and Brazil. ‘Group III’ represent countries that both urban and rural population would decrease, mainly including countries in Eastern Europe and Japan (Extended Data Fig. 1). As a general principle, population density in urban areas is higher than that in rural areas, leading to land release when rural-to-urban migration occurs at regional scale. Despite it may increase exposure of more people to higher pollutant concentrations in densely populated cities, co-benefits have also been identified for resource use, such as energy consumption and its related emission of carbon dioxides per capita.

If urbanization levels were to remain unchanged at 2020 levels (i.e. at 56%), total urban population would increase by 0.9 billion by 2050, which would require an increase of urban land use by 6 Mha (Table 1) (assuming population density was stable as well). Total rural population would increase by 1.1 billion, with rural built-up areas increasing by 39 Mha (Table 1). In total, to settle the total global population with a projected growth of 2 billion from 2020 to 2050 without urbanization, an additional land area of 46 Mha would be required, 86% of which would mainly be needed to settle the increased rural population (Table 1). The largest land requirement is identified for rural areas in Group I countries, due to their relatively large rural population increase and low rural population density, followed by the rural areas in Group II countries. Due to the relatively low urbanization levels in Group I and II countries, an increase in urban population would only require additional land area of 7 Mha (Table 1). Group III countries show
decreasing population levels for both urban and rural areas, leading to an overall decrease in the requirement for land area (Table 1).

### Table 1
Changes of population and land use from 2020 to 2050.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Group</th>
<th>Population (billion)</th>
<th>Land use (Mha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>urban</td>
<td>rural</td>
</tr>
<tr>
<td>BAU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>DOM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>1.2</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>2.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>INT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.7</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>1.8</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>0.0</td>
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</tr>
<tr>
<td></td>
<td>All</td>
<td>2.6</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

The Scenarios are described in Extended Data Table 1. The countries’ spatial distributions of each group are shown in Extended Data Fig. 1. BAU represents business as usual; DOM represents the scenario of domestic migration; INT represents the scenario of cross-country migration. Group I: Both increase in urban and rural population in these countries. Typical countries include Nigeria, Angola, Pakistan, Tanzania and Iraq. Group II: Urban population would increase while rural population would decrease in these countries. Typical countries include China, Russia, United States, India, France, Germany and Brazil. Group III: Both urban and rural population would decrease in these countries. Typical countries include Ukraine and Japan. All represents the sum of these three groups.

The DOM scenario assumes that global urbanization levels increase from 56–68% and rural-to-urban migration is only allowed within country. Under this scenario, total urban population would increase by 2.3 billion and rural population decrease by 0.3 billion by 2050. The increase in urban population levels requires an additional 19 Mha of built-up areas, while the decrease of rural population would release 68 Mha of previously built-up land area in rural areas, resulting in a net land release of 49 Mha (Table 1). The large land release in rural area in Group II countries occurs due to the large number of rural people moving to urban areas. Particular hotspots of urban expansion are found across Asia, Africa, Western Europe and
North America (Fig. 1a), while hotspots of urban shrinking mainly occur in Eastern Europe and Japan (Fig. 1a) due decreasing of urban populations. Rural expansion is mainly observed in Africa, Western Asia and Central Asia, with generally higher rural population levels (Fig. 1b), while rural shrinking is prevalent across the rest of the world due to decrease of rural population, mainly in Asia, Europe and North America (Fig. 1b).

Finally, for the INT scenario, we assume that rural-to-urban migration is allowed across country boundaries. In order to assess options for saving lands and built-up infrastructure in urban areas, we assumed neither rural expansion nor urban shrinking would occur. As a consequence, the increased population in 2050, which has been attributed to rural growth in DOM, is instead allocated to urban areas, and areas where urban shrinking occurs in DOM are filled by transferring growth of rural population. In this scenario, urban population overall would increase by 2.6 billion, while rural population decreases by 0.6 billion, leading to a relatively higher degree of urbanization, i.e. 72%, compared to the DOM scenario (68%). Urban built-up areas increase by 23 Mha (Table 1) due to urban population increases in countries with high population density, mainly in group I and II countries, such as in Asia and Europe (Fig. 1c). Rural built-up areas would decrease by 90 Mha due to a much reduced rural population and thus a reduction of rural built-up areas with comparatively low population density, mainly in group II countries. This leads to a net release of built-up lands of 67 Mha for both urban and rural built-up areas combined (Table 1). Compared to the DOM scenario, the release of rural built-up area in the INT scenario stem from a majority of global regions including Sub-Saharan Africa, and hotspots are mainly located in Asia, Europe and North America (Fig. 1d).

**Food Security**

If these released land areas were used for food production, this would increase croplands by 56 Mha, equivalent to 3.6% of cropland area in 2020 (Fig. 2a and Fig. 3a). Given that built-up area expansion normally follows the principle of contiguity, 17 Mha of natural land areas would be occupied by built-up area expansion as a result of population growth, mainly in Western Africa and North America (Fig. 2a). It means that there would be potentially extra 17 Mha built-up lands could be released for food production due to displacement of built-up lands globally. Similarly, displacement of croplands is also found with urbanization and the increases of cropland areas mainly occur in Eastern Asia and Eastern Europe, while decreases are mainly found in Africa and Western and Southern Asia (Fig. 2a and Fig. 4a). However, approximately 10 Mha of released built-up lands are not considered suitable for farming due to climate constraints and thus could only be restored to grasslands which could be used for livestock production through grazing (Fig. 2a). It suggests that only 7 Mha of extra released built-up lands due to displacement with urbanization could be used for food production (Fig. 3a). The displacement of croplands leads to changes of weighted average cropland yield, indicated by the net primary production (NPP) of these changes of distribution of croplands (Fig. 4c). Global crop production overall would increase by 382 million tonnes (Fig. 3b), equivalent to 3.9% of total crop production in 2020, 0.3% higher than the increase in cropland area. It suggests that the displacement of croplands increases the global
average crop yield given the released lands have better condition for crop production compared to that of the lands taken by urbanization. The increase of crop production mainly occurs in Asia, Europe and North America, which could improve crop self-sufficiency, especially in Asia with large total population (Extended Data Fig. 2b)\(^\text{15}\). A decrease of crop production is mainly projected for Africa and Western and Southern Asia, and may worsen food security and malnutrition challenges in that region (Extended Data Fig. 2a)\(^\text{15}\). This regional variation in projected changes indicates that more international food trade would be needed to balance the food supply and demand among different global regions in the DOM scenario\(^\text{16}\).

In the INT scenario, global cropland area would increase by 74 Mha, equivalent to 4.7% of cropland area in 2020 (Fig. 3a), if all built-up land released is reclaimed for crop production (Fig. 2b). Similar to the DOM scenario, the displacement of built-up lands would also release 7 Mha extra lands for crop production with the consumption of natural lands (Fig. 3a). Compared to the DOM scenario, the impact of built-up area expansion on natural land area would be minimized, with built-up lands displacement only consuming about 10 Mha of natural land by 2050, and 3 Mha of released built-up lands unsuitable to be reclaimed for croplands would be restored to grassland (Fig. 2b). The INT scenario projects a higher degree of preservation of croplands in Africa due to a limited increase of rural built-up areas, leading to an overall increase of cropland in tropical regions (Fig. 4b). Compared to the DOM scenario, the INT scenario results in a higher cropland area per capita in tropical regions, benefiting food security there. Cropland consumed by built-up area expansion is estimated at 12 Mha, mainly located in Eastern Asia, India and Europe (Fig. 2b). This displacement of croplands results in an increase in the average cropland NPP at global scale (Fig. 4d), with crop production increasing by 527 million tons as a result (Fig. 3b), equivalent to 5.4% of crop production in 2020, primarily from Asia, Europe and North America (Fig. 4f).

In addition to the projected increase in crop production, we found that land release from urbanization could reduce cropland fragmentation, benefiting the implementation of advanced agricultural management practices\(^\text{17,18}\). Although it is difficult to estimate specific changes of farm size as a consequence of urbanization for each country globally, the changes in cropland area per rural resident (CAPR) could be used as an indicator of future change in cropland fragmentation. In the DOM scenario, CAPR would increase by 14.4% on a global scale due to a total cropland area increase by 3.6% and rural population decrease by 9.5%. Eastern Asia and East & Middle Europe see the largest increase due to the high potential for rural-to-urban migration (Fig. 4g). This reflects a potential benefit for increasing sustainable agriculture with more food and less environmental damages in smallholder dominated countries\(^\text{18,19}\). Meanwhile, a large number of regions with no substantial rural populations would offer the potential for large-scale farming, such as in North Asia, Middle of South America. At the same time, total cropland area in Sub-Saharan Africa would be reduced due to the increase in rural population, leading to a substantial reduction of CAPR, which may further deteriorate the agricultural sustainability and food security in Africa\(^\text{20,21}\). In the INT scenario, the CARP would increase by 26.6% at global scale, mainly due to total cropland area increasing by 4.7% and rural population decreasing by 17.3%. Compared to the DOM scenario, substantial positive changes of the CARP are found in the Sub-Saharan
Africa, due to rural population migration to other global regions. This would preserve cropland areas and increase the potential for modern, large-scale farming methods which could optimize the use of fertilizers to generate higher yields and thus benefit the food security\textsuperscript{17,18}. Japan and Eastern Europe would see the largest increase of the CARP (Fig. 4h), further increasing farm size\textsuperscript{19} and benefiting agricultural sustainability there\textsuperscript{22}.

**Nature Restoration**

If these released lands are not used for food production, but for nature restoration, what could their contribution to carbon sequestration and to halting biodiversity loss be? We assume all these released lands are used for nature restoration, which represents the largest potential contribution from urbanization-induced land use change. In the real-world, there is a wide spectrum between maximum potential for food production on the one hand and nature restoration on the other hand. We assume that potential areas for forest restoration are mainly located in areas with annual precipitation above 400 mm (Extended Data Fig. 3a), including Eastern and Southern Asia, Eastern Europe, Eastern of North America and Eastern of South America (Fig. 5a and b). Areas with the potential for grassland restoration are mainly located in areas with annual precipitation between 200–400 mm (Extended Data Fig. 3a), including Middle Asia and Western of North America (Fig. 5a and b). The areas for tundra restoration are mainly located in arctic, frigid areas, including North of Canada and Russia (Fig. 5a and b).

In the DOM scenario, global natural land area would increase by 61 Mha, equivalent to 0.6\% of natural land area in 2020. Nature restoration would increase carbon sequestration by vegetation by 328 Tg yr\textsuperscript{-1} (Fig. 3c), with hotspots in Southeast Asia and South America due to relatively higher NPP of forest ecosystems and higher annual mean temperature (Fig. 5c and Extended Data Fig. 3b). However, for Sub-Saharan Africa, a decline in the forest area in Africa and an increase of rural populations would result in a decline of vegetation carbon sequestration. Soil carbon sequestration increases by 2 Pg from 2020 to 2050 (Fig. 3c), mainly in Northern Europe, Canada and the Qinghai-Tibet Plateau, where the lower annual mean temperature benefits a reduction in the decomposition of soil carbon stocks (Fig. 5e). Long-term carbon sequestration (vegetation and soil) could reach 11 Pg over the period from 2020 to 2050. Built-up area expansion could lead to a decline in species richness by 6,593, while nature restoration could lead to a species richness increase by 8,583, resulting in a net increase in total species richness by 1,990 (Fig. 3d), mainly in Southeast Asia and South America (Fig. 5g).

In the INT scenario, the global natural land area would increase by 79 Mha, equivalent to 0.8\% of natural land area in 2020. Compared to the DOM scenario, areas of forest restoration would expand in Africa and Southern Asia (Fig. 5b). Restoration is projected to increase vegetation carbon sequestration by 13 Pg, and soil carbon sequestration by 2 Pg (Fig. 3c). Long-term total carbon sequestration (vegetation and soil) would reach 15 Pg by 2050. Built-up area expansion could lead to a species richness decline by 5,689, while nature restoration could lead to a species richness increase by 10,177, a net increase of
4,488 (Fig. 3d). Compared to the DOM scenario, vegetation and soil carbon sequestration, species richness all increase in Sub-Saharan Africa (Fig. 5d, f and h).

Feasibility And Policy Implication

The mismatch of spatial distribution of population and land uses are at the root of low efficiency of land uses. The process of relocating populations through urbanization generates opportunities for more sustainable land use and land management. However, compared to only relocating livestock production for agricultural sustainability\(^{23}\), it is more challenging to manage human population relocation, due to the complexity around interconnected socioeconomic issues. Multiple stakeholders need to be included in this process and new policies are required to encourage the reclamation of homesteads and migration to cities. According to an OECD report, Malta, Japan, Cyprus, Hungary, the United States, Brazil, Finland, Chile, and Slovenia all have dwelling vacancy rates above 10% (Extended Data Fig. 2c), with rural vacancy rates typically being much higher than those in urban areas\(^ {24}\). According to the data from the Survey and Research Center for China Household Finance, the dwellings vacancy rate is 21% in urban areas\(^ {25}\) in China. So-called “hollow villages” are commonly found across China, especially in areas far from the big urban centers. Thus, there is potential and feasibility to maximumly use the dwellings in urban areas while reclaim rural homestead to increase the land use efficiency for continue growth of global population.

Dwellings vacancy does not only waste resources, but can also a create a range of societal problems, such as increased crime rates\(^ {26}\). Managing urban vacancies is crucial for both fostering new migration from rural areas to cities, and the reclamation of land for food production, especially for Group III countries. There are few examples on urban built-up land reclamation, and here we take the city of Detroit as a case study to analyze the feasibility and potential policy implications. The city of Detroit, Michigan, published a task force plan in 2014 to address blight removal of 84,641 structures and vacant lots at a cost of US$ 850 million. Neighborhood structures make up 98% of the total blighted structures in Detroit, the average demolition cost ranging from US$ 8,500 to US$ 16,000. Detroit has spent US$ 43.5 million to demolish 2,171 structures since 2021\(^ {27}\). Urban agriculture in Detroit occurs at small scale in the vacant lots that were demolished, and is still facing barriers of land tenure, legacy pollutants and lack of government support\(^ {28}\). Soil lead tests completed by Keep growing Detroit in 2004 and 2013 showed that 84% of the sites sampled were safe for growing crops (< 320 ppm)\(^ {29}\). However, in general, soil contamination remediation is necessary if urban agriculture is to be expanded in the future, and in-situ remediation of lead-contaminated soils is considered the most cost-effective method, with costs of about US$ 60,000 ha\(^{-1}\)\(^ {30}\).

Typical examples of rural land reclamation in China, where over 40,000 ha of land have been reclaimed since 2010, mainly in Northeast and Northwest China, the North China Plain, and the Middle and Lower Yangtze River Plain, at an average cost around US$ 23,000 ha\(^{-1}\) (US$ 3,000–50,000 ha\(^{-1}\)\(^ {10}\). Extended Data Fig. 4 shows rural land reclamation in Hetoudian Town, Qingdao City, where more than half of the
rural homesteads have been reclaimed and are gradually becoming contiguous with the surrounding farmland. Although one-time investment costs for built-up area reclamation are high, new croplands can bring crop production benefits and new natural land generate carbon sink benefits in the coming decades. Those accumulating benefits could soon exceed the initial investment costs realizing a net societal benefit. Given this potential as a net-beneficial solution, rural reclamation should be implemented in many global regions beyond China, especially in countries already undergoing rapid urbanization with large rural populations. Given the relatively low implantation costs during initial investment compared to the long-term benefits, direct policy support to incentivize the movement of new migrants to cities could further alleviate new arrivals’ risk to remain in poverty and slum living conditions. In China, social insurance is used as a policy mechanism to facilitate the trade farmers’ homesteads and their croplands, while urban low-rent housing provision by government to new migrants, as well as ensuring access to medical care and education services.

Compared to the DOM scenario, the INT scenario requires more land to be reclaimed overall, but less new built-up area generated at a per person level. The results of relocation of global population is that rural population from Group I would be reduced while urban population in Group III would be increased, which would improve the dwelling occupancy in shrinking urban areas in countries with aging/shrinking populations. It avoids the demolition and newly building of dwellings, and meanwhile save the croplands and natural lands that would be taken for built-up land uses. Group III countries experience population aging, with associated socioeconomic challenges. Cross-countries migration would not only alleviate the aging issues in Group III countries, but also contribute to the achievement of Zero Hunger sustainable development goal due to better distribution of people and food production globally. The better, more balanced, spatial distribution of population and food production would also benefit international food trade and reduce transport energy consumption globally, benefiting energy security and contributing to achieving NetZero goals. Global agreements on cross-countries migration would require policies and financial supports to help the new immigrants to adapt the new environment, promoting the achievement of community with a shared future for mankind on the Earth.

**Methods**

Land use change simulations (including urban expansion, rural expansion, urban reclamation and rural reclamation) are based on the following assumptions: (1) abandoned built-up areas only arise from areas built-up in 2020, while other land use types and new expansion built-up areas are excluded; (2) new built-up areas can occupy surrounding cropland and natural land (sloping areas and water bodies are excluded); and (3) population movement is limited to domestic or international, depending on the scenario setting. Population density in the new expanded urban and rural built-up areas is set to the same level as that in adjacent urban and rural built-up grid cells, respectively. We apply spatial statistics to each grid cell to determine the priority type of land use change.
Scenarios design. We have designed two scenarios based on different expectations of future global urbanization pathways: Domestic urbanization (DOM) and international urbanization (INT). The DOM scenario assumes that the migration of population from rural to urban areas is confined to within national boundaries. An increase of urban or rural population would lead to the expansion of built-up areas, while an urban or rural population decrease would lead to the abandonment of the built-up areas. The INT scenario assumes that countries cooperate for the goals of food security and nature restoration, and net increase of urban and rural populations in each country in the DOM scenario would move to urban built-up area across countries. According to UN urbanization projections for 2050 and our assumptions for the INT scenario, the global urban population would increase while the rural population would decrease, so that the global urban built-up area would only increase while the rural built-up area would only decrease in the INT scenario.

Urban expansion. The prediction of global built-up area expansion and reclamation are based on the land use map in 2020 from the Globeland30 platform with a resampled resolution of 1×1 km^3 (Extended Data Fig. 5). We use the class “artificial land” to represent “built-up area” in this study. According to the definitions of urban and rural area in the Global Human Settlement Layer-Settlement Model (GHSL-SMOD) dataset, built-up area can be reclassified to distinguish seven hierarchical levels: urban center, dense urban cluster, semi-dense urban cluster, suburban, rural cluster, low density rural and very low density rural (Extended Data Fig. 6). Predicted urbanization data is derived from the UN, population spatial gridded dataset in 2020 and derived from WorldPop platform. For every grid cell with the potential to be converted to new urban areas, we set 20×20 grids around “urban center” grids and counted the total number of built-up area grids to calculate their built-up area density (\( \rho \)).

\[
\rho = \frac{c}{20 \times 20} (l)
\]

‘c’ is the number of urban grids in 20×20 grids around the center grid that has potential to become new urban, and ‘\( \rho \)’ is built-up area density within 20×20 grids.

The factors considered in the expansion raster priority are built-up area density and population density. We rank the value of built-up area density from high to low for obtaining priority level for each grid has potential to become new urban area. For grids with the same built-up area density value, we ranked them using the level of population density from high to low.

Rural expansion. In the two scenarios, only the DOM scenario includes rural expansion. We simulate of rural expansion by mainly considering transportation aspects. Global roads and waterways data for the year 2020 are derived from OpenStreetMap. We calculate the density of roads and waterways within every grid cell with the potential for rural expansion and set higher priority to grids with higher density to become new rural areas (\( d \)).

\[
d = l_{roads} + l_{railways} + l_{waterways} (\ )
\]
\( l_{\text{roads}} \) (km) is length of roads in a grid, \( l_{\text{railways}} \) (km) is length of railways in a grid, \( l_{\text{waterways}} \) (km) is length of waterways in a grid, ‘d’ is total length of roads, railways and waterways within each grid. We ranked the value of ‘d’ from high to low for obtaining priority level for each grid has potential to become new rural area.

**Abandonment of built-up areas.** In our simulations, the priority of built-up area abandonment is determined by hierarchical levels of built-up area (from “very low density rural” to “urban center”) and the specific population density of each grid. For grids with the same built-up area hierarchical levels, we ranked them using specific population density of each grid from low to high. In the two scenarios, only the DOM scenario features both urban and rural abandonment of built-up areas. In the INT scenario, only rural built-up areas would be abandoned due to overall changes in rural population levels.

**Reclamation of cropland and restoration of natural land.** For cropland reclamation, we exclude two types of land: (1) lands with an elevation > 3500 m or with a slope > 30° for terrain considerations; (2) land areas that are close to grasslands or bare land with an annual precipitation < 400 mm. We restore uninhabited lands that are close to grasslands and with an annual precipitation between 200–400 mm to grassland. Land areas that are close to bare land with annual precipitation < 200 mm are abandoned. For nature restoration, we assumed that natural land will be restored to the nearest natural vegetation type. We use climate data from Climatic Research Unit gridded Time Series version 4 (Extended Data Fig. 3).

**Crop production and carbon sequestration of natural vegetation.** We use a MODIS-based, annual, year-end gap-filled NPP product (MOD17A3HGF20 v006)\(^4\) for analyzing yield change (Extended Data Fig. 7). Weighted average cropland yield is calculated by the ratio of the sum of NPP of all croplands to the total area of croplands. Since there is no NPP data available for the impervious layer, we assume NPP of newly reclaimed cropland to be equal to the NPP of closest existing cropland, and the NPP of newly restored natural land is equal to the NPP of the closest existing natural land. We calculate the increase in global food production by 2050 assuming that the ratio of global food production (million tons) to net primary productivity of cropland (Tg C) remains constant over the period from 2020 to 2050. We calculated changes of NPP and natural land vegetation carbon sequestration by the product of cropland/natural land area change and average NPP change.

\[
CP = \frac{area_2}{area_1} \times \frac{npp_2}{npp_1} (IV)
\]

where \( area_1 \) and \( area_2 \) are cropland area of a country in year\(_1\) and year\(_2\), respectively. \( npp_1 \) and \( npp_2 \) are average NPP of a country in year\(_1\) and year\(_2\). \( CP \) is the ratio of crop production in year\(_1\) and year\(_2\). The effect of agricultural management improvement is not considered here.

**Soil organic carbon sequestration.** We use soil organic carbon stock data (t/ha) for 0–30 cm depth intervals from the International Soil Reference and Information Centre (ISRIC)\(^5\) (Extended Data Fig. 8). We only account for changes in carbon stocks in topsoil (0–30 cm) and assume it can be restored to the level of original natural land in close proximity over a period of 30 years.\(^6\) The soil organic carbon
storage data we obtained did not include built-up areas, and the carbon storage in the reference impervious layer was 50% lower on average than that in nearby open areas\textsuperscript{44}. Therefore, the carbon storage potential of restoring built-up areas to natural land can be calculated using the following formula (V).

\[ SCP = SOC_{natural} - SOC_{openarea} \times 0.5 \quad (V) \]

SCP is soil organic carbon storage potential of restoring the built-up area to natural land, \( SOC_{natural} \) is the soil organic carbon storage of the natural land closest to the built-up area, \( SOC_{openarea} \) is the soil organic carbon storage of the open area (including natural land and cropland) closest to the built-up area.

**Biodiversity.** We only utilize species richness as a single indicator of biodiversity in this study\textsuperscript{45}. We use species richness data compiled from three common terrestrial vertebrate taxa (including amphibians, mammals, and birds) from the IUCN Red List\textsuperscript{46} and BirdLife International\textsuperscript{47}. Due to data limitation, changes of terrestrial vertebrate species richness are calculated only by overlap of land use change grid and species distribution polygons. We only include extant species in calculations.

**Declarations**

**Data availability**

Data supporting the findings of this study are available within the article and its supplementary information files.

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**Author contributions**

B.G. designed the research. S.W. and O.D. conducted the research and performed the analysis. B.G., S.W. and S.R. revised the paper. And all authors contributed to the discussion and revision of the paper. Thanks to X.Z. for their help with the initial discussions and data processing.

**Declaration of competing interest**

All authors have no conflicts of interest to report.

**Additional information**

Extended data is available for this paper.
Supplementary information is available for this paper.

Correspondence and requests for materials should be addressed to B.G.

References


**Figures**
Figure 1

Change of built-up area from 2020 to 2050 under different scenarios. Blue means areas decrease and red means areas increase. a, Urban change in the DOM scenario. b, Rural change in the DOM scenario. c, Urban change in the INT scenario. d, Rural change in the INT scenario.
Figure 2

Changes of cropland and natural land during 2020-2050. The Scenarios are described in Extended Data Table 1. **a,** Cropland and Natural land changes in the DOM and the Food Security scenario. **b,** Cropland and Natural land changes in the INT and the Food Security scenario. **c,** Cropland and Natural land changes in the DOM and the Nature Restoration scenario. **d,** Cropland and Natural land changes in the INT and the Nature Restoration scenario.
Figure 3

Change of land area, crop production, carbon sequestration and biodiversity during 2020-2050 under different scenarios. a, Built-up area, natural land and cropland area change. b, Crop production change under Food Security scenario. c, Carbon sequestration change under Nature Restoration scenario. d, Species richness change under Nature Restoration scenario.
Figure 4

Changes of food security during 2020-2050. a, Changes of cropland area in the DOM scenario. b, Changes of cropland area in the INT scenario. c, Changes of average NPP in the DOM scenario. d, Changes of average NPP in the INT scenario. e, Changes of crop production in the DOM scenario. f, Changes of crop production in the INT scenario. g, Changes of cropland area per rural resident (CAPR) in the DOM scenario. h, Changes of CAPR in the INT scenario.
Figure 5

Changes of nature restoration during 2020-2050. The Scenarios are described in Extended Data Table 1. 

(a) Major types of natural land restoration in the DOM scenario. 

(b) Major types of natural land restoration in the INT scenario. 

(c) Changes of average NPP in the DOM scenario. 

(d) Changes of average NPP in the INT scenario. 

(e) Changes of soil organic carbon storage in the DOM scenario. 

(f) Changes of soil organic carbon storage in the INT scenario. 

(g) Changes of species richness (per grid) in the DOM scenario. 

(h) Changes of species richness (per grid) in the INT scenario.
carbon storage in the INT scenario. g, Average changes of species richness in the DOM scenario. h, Average changes of species richness in the INT scenario.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- [ExtendedDataFigs.docx](ExtendedDataFigs.docx)