Abstract

Large-scale urban expansion worldwide has exerted great impacts on cropland and its net primary productivity (NPP), which can affect whether food security and sustainable development goals will be met at global and local scales. Although important, the impacts at the global scale over the last 25 years remain unclear. Based on the latest long-term dynamic urban expansion data, this study analyzed global urban expansion and its impacts on cropland NPP from 1992 to 2016 at multiple scales. The results showed that the expansion of urban land occupied a total of 159 170 km$^2$ of cropland, accounting for 45.9% of the total expanded urban area. The cropland NPP decreased by 58.71 (56.52 ~ 59.81, 95% confidence interval) TgC as a result of urban expansion, which represents approximately 0.42% (0.40% ~ 0.43%) of the multiyear average of total cropland NPP from 2000 to 2015. If the cropland NPP losses were converted to the grain production (i.e. 1.44 × 10$^7$ tons), it is equivalent to the minimum annual food intake demands for at least 36 million people. More importantly, urban expansion is exacerbating the risk of food security in developing countries in Asia and Africa, such as China, Vietnam and Egypt. In the future, these countries should balance urban expansion with cropland protection by strictly restricting the occupation of cropland and encouraging smart urban growth.

1. Introduction

The world is undergoing a large-scale process of urban expansion (Angel et al 2016). The global urban land area increased from 602 900 km$^2$ in 2000 to 711 800 km$^2$ in 2010 (Angel et al 2011). The expanded area during this time was 1.9 times that from 1970 to 2000 (Seto et al 2011). It has been estimated that from 2000 to 2030, the urban land area will further increase by 335 900 km$^2$. The estimated area of urban expansion is expected to reach 5.8 times that from the previous 30 years, approximately equal to the total area of Italy (Angel et al 2011).

Urban expansion has attracted large populations, many resources and abundant economic activities to cities, which provide important opportunities for improving energy utilization efficiency, optimizing transportation structures and promoting human well-being (Grimm et al 2008, Seto et al 2010). However, urban expansion also occupies fertile cropland surrounding existing urban areas, which reduces the net primary productivity (NPP) of cropland and thus aggravates the food crisis (Shochat et al 2006, Mcdonald et al 2008, Thebo et al 2014). It has been estimated that the global urban expansion from 2000 to 2030 will cause a 1.8%–2.4% loss in cropland area, thus reducing global crop production by approximately 3%–4% (d’Amour et al 2017). Although urban expansion occupies only a small portion of cropland area and has limited impacts on cropland NPP at the global scale, the processes in some countries and regions are directly preventing the local residents from reaching the second goal (i.e. zero hunger) of the Sustainable Development Goals.

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Development Goals (SDGs) by the United Nations (Besthorn 2013; FAO 2018; WHO 2018). Therefore, understanding the impacts of global urban expansion on cropland and its NPP on multiple scales is of great significance for regional food security.

Studies have estimated the potential impacts of future urban expansion on cropland areas and cropland production at the global scale and found that the occupation of cropland by urban expansion would increase the vulnerability of food security in some countries and regions. However, previous studies normally underestimate the impact because of the overlook of cropland productivity, its intensive use (Wu et al 2018) and climate change (e.g. 'global greening', Chen et al 2019). In addition, previous studies mainly focused on estimating the potential impacts in the future while historical studies were mainly conducted at national or regional scales. For example, van Vliet et al (2017) used the CLUMondo model to evaluate the transformation of cropland to urban land from 2000 to 2040. They found that global urban expansion would lead to a loss of 350 000 km² of cropland and a reduction in crop production of 65 million tons. d’Amour et al (2017) estimated the cropland occupied by global urban expansion from 2000 to 2030 and found that urban expansion would cause approximately 1.8%–2.4% and 3%–4% losses in global cropland areas and crop production, respectively. At the national scale, studies have evaluated cropland occupation by historic urban expansion processes in countries such as China (Yan et al 2009; He et al 2017), USA (Zhang et al 2012), India (Pandey and Seto 2015), Nigeria (Nkeki 2016) and Vietnam (Phuc et al 2014). At the regional scale, similar studies were also conducted for Ontario of Canada (Cocklin et al 1983), Puerto Rico (Del Mar López et al 2001), the Pearl River Delta urban agglomeration in China (Wang et al 2014) and Buenos Aires in Argentina (Li 2018). In a word, a global analysis of the impacts of historic urban expansion on cropland areas and cropland production is still lacking.

Our objective is to quantitatively reveal the impacts of global urban expansion on cropland area and its NPP from 1992 to 2016 by using long-term urban expansion data and NPP data. This estimate would account for the difference in cropland productivity and its intensive use, as well as the uncertainty brought by climate change. First, we analyzed the process of cropland occupation by urban expansion from 1992 to 2016 at the global, continental and national scales with support from the latest global urban land dataset. Then, we quantified the impacts of global urban expansion on cropland NPP. Finally, we identified the hotspots where the impacts of cropland occupation by urban expansion were most severe and provided corresponding policy recommendations.

2. Study area and data

2.1. Study area

This study covers six continents, including Asia, Europe, North America, South America, Africa and Oceania (figure 1). In terms of cropland area, the total global cropland area was 14.22 million km² in 2016, accounting for 11.0% of the global land area. At the continental scale, the cropland area in Asia was the largest, reaching 8.45 million km², 59.4% of the...
total global cropland. Croplands were concentrated in India, USA, Russia and China, with areas cumulatively accounting for nearly 40% of the total global cropland (FAO 2018; World Bank 2019). In terms of grain production, the total global grain production in 2016 reached 2.91 billion tons. Asia still has the largest grain production. The grain production in Asia reached 1.41 billion tons in 2016, which was nearly half (48.6%) of the total global sum (FAO 2018). China, USA and India had the top three grain productions, with production cumulatively accounted for nearly half of the total global grain production (FAO 2018).

2.2. Data
The annual global urban land data from 1992 to 2016 were released by He et al (2019). Based on a fully convolutional network under the deep learning framework, the new dataset contains extracted information on urban land areas based on nighttime light data, a vegetation index and land surface temperature data. Compared to existing global urban land datasets, such as the global long-term built-up area dataset released by the Netherlands Environmental Assessment Agency (Klein Goldewijk et al 2010), the global land cover datasets for 2000 and 2010 released by the National Geomatics Center of China (Chen et al 2015) and the global land cover dataset from 1992 to 2015 released by the European Space Agency (UCL-Geomatics 2017), this new dataset exhibits high consistency and greater accuracy in capturing the overall accuracy reach 0.47 and 90.89%, respectively, which are 0.27–0.32 and 0.4%-3.5% higher than those of existing global urban expansion datasets.

Global NPP data from 2000 to 2015 with a spatial resolution of 1 km were acquired from the MOD17A3 data released by NASA’s Earth Observation System Data and Information System. These data were simulated by Zhao and Running (2011) using the Biome-BGC model and a light use efficiency model, and the overall accuracy was 76%. These data have been widely used in research on global and regional NPP and the carbon cycle (Fensholt et al 2006, Street and McNickle 2019).

The cropland data from 1992 to 2015 with a spatial resolution of 300 m were obtained from the Climate Change Initiative-Land Cover (CCI-LC) dataset released by the European Space Agency (ESA) (UCL-Geomatics 2017). This dataset includes six types of land uses (cropland, forest, grassland, wetland, settlement and other), and each type of land use has an overall accuracy between 83% and 96%. This dataset has been widely used to study land use change and its impact at the global scale (Xu et al 2019). Although there are differences in delineating cropland between the CCI-LC dataset and MODIS landcover dataset, a global comparison also found that they are highly consistent (Sakti et al 2017). We further aggregate the extent of cropland within each 1 km cell and convert the original binary information (1 for cropland and 0 for non-cropland) to a fractional information (e.g. 0.8).

Global grain production from 2000 to 2015 came from the Food and Agriculture Organization (FAO) of the United Nations (FAO 2019). The cropland areas in 2016 were released by the World Bank (https://data.worldbank.org). The global, continental and national boundaries came from the Institute of Geographic Sciences and Natural Resource Research, Chinese Academy of Sciences (www.resdc.cn/data.aspx?DATAID=205).

3. Methods

3.1. Quantifying the dynamics of urban expansion
First, we calculated the urban land area at the global, continental and national scales. Then, we analyzed the process of urban expansion from 1992 to 2016 with two indicators: the changes in urban land and the urban land growth rate. The former is calculated as follows:

\[ \text{Urb}_{A,t} = A_{t_2} - A_{t_1}, t_2 > t_1 \]

where \( \text{Urb}_{A,t} \) denotes the change in urban land from \( t_1 \) to \( t_2 \); \( A_{t_1} \) and \( A_{t_2} \) are the areas of urban land in \( t_1 \) and \( t_2 \), respectively. The equation for the urban land growth rate (\( R_{(t_1,t_2)} \)) is calculated following Gao et al (2016) as below:

\[ R_{(t_1,t_2)} = \left( \frac{A_{t_2}}{A_{t_1}} \right)^{\frac{1}{t_2-t_1}} - 1 \times 100\%, t_2 > t_1. \]

3.2. Analyzing cropland occupation by urban expansion
The croplands occupied by urban expansion were extracted by overlapping the land use dataset for 1992 released by the ESA with a dynamic urban expansion dataset, following the method by He et al (2017). The procedure was conducted in ESRI ArcMap 10.4 (see supplementary 1, available online at https://stacks.iop.org/ERL/15/084037/mmedia).

3.3. Measuring the impact of urban expansion on cropland NPP
We assessed the loss in cropland NPP caused by urban expansion based on the method of Milesi et al (2003), in which the loss was estimated by overlapping the NPP data before urban expansion with global land use data and urban expansion data from 1992 to 2016. Considering the trend of ‘global greening’ by CO₂ enhancement (Chen et al 2019), we used the long-term average values of MODIS NPP as a proxy to estimate the impacts of urban expansion on cropland NPP. We also reported the 95% confidence intervals to represent the uncertainties caused by climate change and global greening. This process can be
expressed using the following equation:

$$CNPP^{\text{loss}} = \sum \left( CA_{i}^{1992} \times NPP_{i}^{2000-2015} \times (Urban_{i}^{2016} - Urban_{i}^{1992}) \right)$$

where $CNPP^{\text{loss}}$ is the loss in cropland NPP caused by urban expansion from 1992 to 2016 and the unit is TgC; $NPP_{i}^{2000-2015}$ refers to the multiyear average of NPP per km$^2$ of the $i$th pixel from 2000 to 2015.

### 4. Results

#### 4.1. Global urban expansion

The world has undergone a large-scale process of urban development. From 1992 to 2016, the global urban land area increased from $2.75 \times 10^5$ km$^2$ to $6.22 \times 10^5$ km$^2$, representing a 2.3-fold increase in urban land. The expanded areas of urban land reached $3.47 \times 10^5$ km$^2$, with an annual growth rate of 3.5%. This number is consistent with a recent estimation that indicated that the global increase in urban land from 1992 to 2015 reached $3.81 \times 10^5$ km$^2$ (van Vliet 2019). During the last 25 years, the fastest period of urban expansion occurred during 1992–1996, with an annual growth rate of 9.2%. During 1996–2000, 2000–2006 and 2006–2010, urban expansion slowed, with annual growth rates of 4.4%, 1.9% and 2.7%, respectively. The latest speed of urban expansion (2010–2016) was the slowest, with an annual growth rate of 1.3%.

The newly expanded urban area concentrated within mid- and high-latitude of north hemisphere (figure 2(a)). At the continental scale, the increase in urban land areas was the largest in Asia, increasing from $6.59 \times 10^4$ km$^2$ in 1992 to $2.10 \times 10^5$ km$^2$ in 2016 and accounting for 41.6% of the total global growth (table 1). The areas of urban land in North America, South America and Europe, increased by $6.97 \times 10^4$ km$^2$, $6.34 \times 10^4$ km$^2$, and $3.99 \times 10^4$ km$^2$, respectively, which correspondingly accounted for...
Table 1. Croplands occupied by urban expansion on multiple scales from 1992 to 2016.

| Regions  | Area of urban expansion |  |  | Cropland area occupied by urban expansion |  |  |
|----------|-------------------------|---|---|------------------------------------------|---|---|
|          | Areas (10^3 km^2)       | % |    | Areas (10^3 km^2)                      | % |    |
|          | Proportion of global total (%) |  |    | Proportion of total global loss (%) |  |    |
|          | Change rate^a   |  |    | Proportion^b (%) |  |    |
| Global   | 346.81                | 100 | 1.3 | 159.17                                      | 100 | 6.3 |
| Asia     | 144.1                 | 41.6 | 2.2 | 82.88                                      | 52.1 | 9.0 |
| South    | 63.44                 | 18.3 | 1.7 | 25.72                                      | 16.2 | 5.1 |
| America  |                       |    |    |                                           |    |    |
| Europe   | 39.88                 | 11.5 | 0.5 | 25.67                                      | 16.1 | 7.2 |
| North    | 69.72                 | 20.1 | 0.9 | 17.73                                      | 11.1 | 7.3 |
| Africa   | 19.89                 | 5.7  | 2.5 | 5.73                                       | 3.6  | 1.2 |
| Oceania  | 9.77                  | 2.8  | 2.0 | 1.43                                       | 0.9  | 2.1 |
| China    | 72.52                 | 20.9 | 4.5 | 42.19                                      | 26.5 | 15.5 |
| USA      | 66.41                 | 19.1 | 0.9 | 16.03                                      | 10.1 | 8.5 |
| Brazil   | 28.92                 | 8.3  | 1.9 | 14.04                                      | 8.8  | 7.6 |
| India    | 14.56                 | 4.2  | 1.8 | 10.36                                      | 6.5  | 4.7 |
| Argentina| 11.42                 | 3.3  | 2.1 | 5.27                                       | 3.3  | 8.6 |
| Russia   | 3.59                  | 1.0  | 0.2 | 4.04                                       | 2.5  | 2.2 |
| Italy    | 5.52                  | 1.6  | 0.7 | 3.86                                       | 2.4  | 23.6 |
| Turkey   | 7.43                  | 2.1  | 4.6 | 3.6                                        | 2.3  | 8.1 |
| Vietnam  | 4.47                  | 1.3  | 22.9| 3.39                                       | 2.1  | 22.8 |
| Spain    | 5.29                  | 1.5  | 1.8 | 2.96                                       | 1.9  | 11.0 |

Note: Change rate refers to the expanded urban land during 1992–2016 divided by urban land in 1992; Proportion means the proportion of cropland displacement by urban expansion to total cropland.

4.2. Cropland displacement and NPP losses by urban expansion

Globally, almost half of the urban expansion took place in cropland. From 1992 to 2016, urban expansion occupied a total of 1.59 × 10^5 km^2 of cropland, accounting for 45.9% of the total urban expansion area (table 1). This number is consistent with a recent estimation that indicated that 44.6% of the global urban expansion involved encroachment onto cropland (Liu et al 2019b). The occupation of cropland by urban expansion concentrated in the eastern hemisphere and within mid- and high-latitude of north hemisphere (figure 3(a)). At the continental scale, Asia experienced the largest occupation of cropland by urban expansion. Over the past 25 years, urban expansion in Asia has occupied 8.29 × 10^4 km^2 of cropland, which accounted for 57.5% of the total area of urban expansion in Asia and 52.1% of the total occupation of cropland by urban expansion worldwide (table 1, figure 3(b)). The occupations in South America and Europe were smaller than those in Asia, both of which were 2.57 × 10^4 km^2, accounting for 40.5% and 64.4% of the total urban expansion areas in South America and Europe, respectively. For the proportion of cropland displacement by urban expansion to total cropland, Asia, North America, and Europe ranked the top three, with values of 9.0‰, 7.3‰, and 7.2‰, respectively (table 1).

At the national scale, more than half of the losses in cropland due to urban expansion were concentrated in China, USA, Brazil, India and Argentina (figures 3(a) and (c)). The total area of cropland displaced by urban expansion in those five countries reached 8.78 × 10^4 km^2, accounting for 55.2% of the total occupation worldwide. Among them, China witnessed the largest cropland losses from urban expansion. Over the past 25 years, the cropland area occupied by urban expansion in China reached 4.22 × 10^4 km^2, which represents 58.2% of the total expanded urban land in China, 26.5% of the total cropland occupation by urban expansion worldwide.
These findings were also consistent with a previous study (Ju et al. 2018), which indicated that from 1987 to 2010, $4.28 \times 10^4$ km$^2$ of cropland was converted into urban land in China. The cropland areas occupied by urban expansion in USA, Brazil and India all exceeded 10,000 km$^2$. From the perspective of the proportion of cropland displacement by urban expansion to total cropland, Italy, Vietnam, and China ranked the top three, with values of 23.6‰, 22.8‰, and 15.5‰, respectively (table 1).

Global urban expansion has caused substantial cropland NPP losses. From 1992 to 2016, urban expansion resulted in cropland NPP losses of approximately 58.71 (56.52 ~ 59.81, 95% confidence interval) TgC, accounting for approximately 0.4% of the multiyear average of total cropland NPP from 2000 to 2015 (table 2). The cropland NPP losses due to urban expansion also concentrated within mid- and high-latitude of north hemisphere (figure 4). At the continental scale, over two-thirds of the cropland NPP losses by urban expansion were concentrated in Asia (22.57, or 21.66 ~ 22.72 TgC) and South America (15.21, or 14.53 ~ 15.97 TgC) (figure 4), which together accounted for 64.4% of the total cropland NPP loss worldwide. In North America, Europe, and Africa, the cropland NPP losses were 9.51 (9.46 ~ 9.53) TgC, 8.94 (8.65 ~ 8.97) TgC, and 1.71 (1.50 ~ 1.76) TgC, respectively. For the proportion of cropland NPP losses to total cropland NPP, North America, South America and Asia ranked the top three, with values exceeding 5.0‰.

At the national scale, China, Brazil, USA, Argentina and India were the top five countries with the largest cropland NPP losses due to urban expansion (table 2). These five countries experienced a total loss of 33.85 (32.47 ~ 34.63) TgC in cropland NPP

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**Figure 3.** Cropland area occupied by urban expansion on multiple scales from 1992 to 2016. (a) global distribution, (b) continental scale, (c) national scale. Note: the bar plot in (a) represents cropland urban expansion along longitudes and latitudes.
Table 2. Cropland NPP losses due to urban expansion on multiple scales from 1992 to 2016.

| Regions       | Quantity (TgC) | Proportion of global total (%) | Average cropland NPP losses due to urban expansion | Proportion of total global loss (%) | Proportion of cropland losses to total cropland NPP (%) |
|---------------|----------------|--------------------------------|---------------------------------------------------|-----------------------------------|--------------------------------------------------------|
|               |                |                                | Quantity (95% confidence interval) (TgC) | Proportion of total global loss (%) | Proportion of cropland losses to total cropland NPP (%) |
| Global        | 14 049.49      | 100                            | 58.71 (56.52–59.81) | 100                               | 4.2 (4.0–4.3) |
| Asia          | 4388.68        | 31.2                           | 22.57 (21.66–22.72) | 38.5                              | 5.1 (4.9–5.2) |
| South America | 2713.63        | 19.3                           | 15.21 (14.53–15.97) | 25.9                              | 5.6 (5.4–5.9) |
| North America | 1646.47        | 11.7                           | 9.51 (9.46–9.53)    | 16.2                              | 5.8 (5.7–5.9) |
| Europe        | 2342.64        | 16.7                           | 8.94 (8.65–8.97)    | 15.2                              | 3.8 (3.7–3.9) |
| Africa        | 2522.2         | 18.0                           | 1.71 (1.50–1.76)    | 2.9                               | 0.7 (0.6–0.8) |
| Oceania       | 435.87         | 3.1                            | 0.76 (0.73–0.86)    | 1.3                               | 1.7 (1.6–2.0) |
| China         | 1315.83        | 9.4                            | 11.60 (11.22–11.71) | 19.8                              | 8.8 (8.5–8.9) |
| Brazil        | 1754.88        | 12.5                           | 10.68 (10.01–11.13) | 18.2                              | 6.1 (5.7–6.3) |
| USA           | 928.04         | 6.6                            | 6.72 (6.50–6.74)    | 11.5                              | 7.2 (7.0–7.3) |
| Argentina     | 367.68         | 2.6                            | 2.58 (2.53–2.71)    | 4.4                               | 7.0 (6.9–7.4) |
| India         | 733.73         | 5.2                            | 2.27 (2.21–2.34)    | 3.9                               | 3.1 (3.0–3.2) |
| Vietnam       | 114.47         | 0.8                            | 1.79 (1.76–1.81)    | 3.0                               | 15.6 (15.4–15.8) |
| Italy         | 134.58         | 1.0                            | 1.47 (1.46–1.48)    | 2.5                               | 10.9 (10.8–11.0) |
| Mexico        | 239.35         | 1.7                            | 1.44 (1.43–1.52)    | 2.5                               | 6.0 (5.9–6.4) |
| Russia        | 746.95         | 5.3                            | 1.16 (1.11–1.23)    | 2.0                               | 1.6 (1.5–1.7) |
| Malaysia      | 89.61          | 0.6                            | 1.15 (1.12–1.21)    | 2.0                               | 12.8 (12.5–13.5) |
Figure 4. The global distribution of loss in cropland NPP due to urban expansion from 1992 to 2016.

5. Discussion

5.1. The impact of urban expansion on grain production exhibited regional differences

Understanding the spatially heterogeneous impacts of urban expansion on food production plays a critical role in the achievement of ‘zero hunger’ by various countries and regions. Thus, we estimated that if all the cropland NPP losses were used to grow grain crops, how much grain production can they produce. When we converted the NPP to grain production, we considered the heterogeneity of cropland production among nations by using the FAO statistics to estimate the national average harvest index (which is affected by cropland intensive use and management) following the study of Ju et al. (2010). This method is more accurate than previous methods which used the NPP to proxy food production loss (Yan et al. 2009), or used a given coefficient worldwide to convert the NPP to food production. Specifically, we converted the cropland NPP losses to grain production using the coefficient for converting carbon content to dry matter and the multiyear average harvest frequency index for each country and region from 2000 to 2015 (see supplementary 2). We did not consider the difference in specific crops (e.g. rice, wheat, and maize) but used the average harvest frequency index for simplicity. By using this method, we can eliminate the impacts of climate fluctuation. More importantly, it can account for the cropland intensification and management as it used the actual grain production data and annual cumulative NPP data to estimate the average harvest frequency index for each country.

Asia had the largest volume of grain production if these NPP losses were used to grow grain crops (figure 5). The total volume of grain production by these croplands in Asia amounted to 7.38 × 10^6 tons (7.00 × 10^6 ~ 7.50 × 10^6 tons), which accounted for 51.2% of the total production. Meanwhile, the cropland NPP losses in Asia were 22.57 (21.66 ~ 22.72) TgC, which accounted for 38.5% of the total global loss. Obviously, the proportion of assumed grain production in Asia to the total production (51.2%) was much greater than the proportion of cropland NPP loss to the total global loss (38.5%). This phenomenon occurs because the urban expansion in Asia occupied high-yield crop land areas. Specifically, because rice in Asian countries is more prevalent than in other regions and multi-cropped much more often than maize and wheat, the cropland harvest frequency in Asian countries is generally higher than the global average. Such disproportional loss in fertile cropland due to urban expansion is also in line with previous findings (Xiong et al. 2014, Liu et al. 2019a). Similarly, this situation was also true for African countries. Specifically, the assumed cropland grain production in Africa (6.50 × 10^5 tons, or 5.86 × 10^5 ~ 6.81 × 10^5 tons)
Figure 5. The assumed grain production on multiple scales if the cropland NPP losses by urban expansion from 1992 to 2016 were used to grow grain crops. (a) global distribution, (b) continental scale, (c) the top 10 countries/regions with the largest volumes of the assumed grain production.

Note: the ratios in (b) and (c) are calculated as the division between two proportions. The former proportion is the volume of grain production to global production, while the latter is the loss in cropland to its global total.

Developing countries in Asia and Africa (China, India, Vietnam and Egypt) were also facing the problem that urban expansion occupied high-yield croplands (figure 5(c)). The assumed grain production in China ($4.43 \times 10^6$ tons, $4.05 \times 10^6$ ~ $4.58 \times 10^6$ tons) accounted for 31.6% of the total global production, whereas the portion of cropland NPP loss in China to the total global loss was 19.8%. The former was 1.59 times the latter. Similar situations were also found in India (1.41 times), Vietnam (1.68 times) and Egypt (3.79 times). In other words, urban expansion in these countries...
Figure 6. Relationship between the speed of urban expansion and the change in grain imports and exports among countries. Note: The assumed grain refers to the grain production converted from the cropland NPP losses caused by urban expansion. The data on grain imports and exports in 2016 were obtained from the FAO (2019) for food and feed, including grain crops (rice, maize and wheat) and economic crops (soybean and rapeseed). The horizontal dashed line represents the average annual growth rate of global urban expansion (3.5%).

exerted disproportionately high pressure on grain production by occupying fertile croplands. These findings also supported arguments made by previous studies (Yan et al. 2009, Kong 2014, Liu et al. 2015, van Vliet et al. 2017). Since it is difficult to convert urban land back to fertile cropland, greater attention should be paid to controlling the occupation of fertile cropland by urban expansion in Asian and African countries.

It is also worth noting that, though global urban land occupied a large amount of cropland during 1992–2016, this amount can be offset by global cropland expansion driven by increases in agricultural product prices and croplands replacing pastures and forests, especially in Latin America and North America (Morton et al. 2006, Graesser et al. 2015, Lark et al. 2015). Using the ESA-CCI data, we estimated the expanded cropland during 1992–2016 and the areas reaching 822.07 thousand km², while the decrease in cropland due to urban expansion was 159.17 thousand km². In addition, the increases in NPP by cropland expansion (312.15 TgC) also exceeded the losses (58.71 TgC) caused by urban land occupying cropland. Although cropland expansion can offset the cropland losses caused by urban expansion, it is unsustainable in terms of its efficiency and environmental consequences. Previous studies have found that the new cropland expanded in less fertile land and arid regions need increasing inputs of fertilizers and irrigation (Kehoe et al. 2017, Yu et al. 2018), which led to substantive impacts on biodiversity, water pollution and groundwater depletion. In other words, cropland displacement by urban expansion cannot be offset by cropland expansion in the long run, and its impacts on food production should be scrutinized.

5.2. Urban expansion could lever food security in developing countries in Asia and Africa

Food security is a complex issue involving food availability, accessibility, stability and utilization (Reif et al. 2015, FAO 2018). Among these components, the conflicts between global food demand and limited cropland resources is one of the greatest challenges humanity faces today (Foley et al. 2005, Yao et al. 2017, Dou et al. 2018). According to statistics, global population increased from 5.48 billion in 1992 to 7.43 billion in 2016, a net increase of 1.95 billion (World Bank 2016). Meanwhile, the lifestyle and pattern of
food consumption has changed along with the economic development and urbanization, which also led to a net increase in per capita food demand (Yen et al 2004, Larson 2013). In the context of increasing food demand and limited potential in food production, this study further revealed that urban expansion and its occupation of croplands could exacerbate the food security challenge in developing countries in Asia and Africa.

Specifically, cropland occupation by urban expansion can further aggravate regional food security through multiple channels. First, rapid urban expansion may further exacerbate the issues of hunger and food security regionally and subsequently threaten the achievement of global sustainable development (SDG2). Although the estimated grain production by urban expansion at the global scale ($1.44 \times 10^7$ tons) accounted for approximately 0.73% of the global grain production in 1992 ($1.97 \times 10^9$ tons), it could provide adequate food for a large number of people (FAO 2018). According to the standard from FAO (400 kg food per capita per year), $1.44 \times 10^7$ tons of grain production can meet the survival needs of 36 million hungry people for one year, which is approximately equal to the total population of Afghanistan. Meanwhile, FAO (2018) reported that by 2018, the number of people facing food shortages worldwide reached 822 million. Accordingly, the estimated grain production can feed at least one in 23 hungry people worldwide.

Second, cropland losses as a result of rapid urban expansion will potentially increase the risk of food security in developing countries in Asia and Africa, which are highly dependent on food imports. If we compare the annual rates of urban expansion and the volume of imported grain (including food and feed) among nations (figure 6), we can identify that developing countries in Asia and Africa (e.g. China, Egypt and Vietnam) have shown higher speeds of urban expansion and larger amounts of grain imports than the global average. In China, the annual growth rate of urban expansion was 7.4%, which is 2.12 times the global average. Meanwhile, the estimated grain production produced by the cropland occupied by urban expansion reached $4.43 \times 10^9$ tons, which is equivalent to the total annual grain production in North Korea, or can meet the basic survival needs of 11 million hungry people for one year. In addition, our analysis also showed that urban expansion in China occupied croplands with higher efficiency of grain production than the global average. In this context, the instabilities in the global price of grain and the obstacles to international free trade can potentially influence food security in China and other developing countries in Asia and Africa (Jongwanich and Park 2011, Berazneva and Lee 2013, Mukhopadhyay et al 2018, Gawith and Hodge 2019).

Third, urban expansion in developing countries in Asia and Africa can interact with issues such as war, political turmoil and climate change, and exacerbate regional food security problems. It is predicted that urban expansion in the future will be concentrated in developing countries in Africa and Asia (Ariti et al 2015, Qader et al 2018), such as Ethiopia, Congo and Pakistan. FAO reported that one in 12 children under five (52 million) suffered from hunger, more than half of whom live in South Asia (27.6 million). In these countries and regions, the croplands will be abandoned, and the grain production will be reduced due to civil war and social unrest, which has greatly hindered food accessibility and will directly threaten the basic survival demands (Abbink 2017, FAO 2018, Landholm et al 2019). Moreover, unfavorable climate conditions, such as continuous drought or flooding, are expected to reduce the arable croplands and average per unit yield of grain across Africa, South Asia and Southeast Asia, resulting in reduced food utilization, which are difficult to overcome by cropland intensification (Fischer et al 2002, Wheeler and Von Braun 2013). Fourth, the replacement of cropland with urban land implies that the per unit yield will need to increase in the remaining cropland to guarantee grain production. However, an increase in the per unit yield of cropland can result in extensive pressure on the environment, such as the pollution caused by pesticides and fertilizers, deterioration of soil quality and overexploitation of groundwater (Liu et al 2013, Lu et al 2015, Zuo et al 2018).

In summary, urban expansion can affect food security in a variety of ways, and developing countries in Asia and Africa are particularly at risk. Therefore, these countries should take effective measures to reduce the impacts of urban expansion on food security. In terms of urban land, it is imperative to limit the urban expansion over fertile cropland, tap the potential of urban agriculture and encourage smart growth to improve the density of urban land (Gu et al 2019). In terms of cropland, we should adjust the planting structure and protect high-quality cropland resources to maintain steady economic growth. Meanwhile, it is necessary to strictly abide by the red line of cropland to guarantee that the basic food demands of local residents are met (Li et al 2016, Mukhopadhyay et al 2018). In addition, sustainable intensification should be encouraged on existing croplands to offset the negative impacts of cropland losses resulting from urban expansion (Zuo et al 2018, Ellis 2019).

5.3. Future perspectives

This study analyzed the impacts of global urban expansion on cropland and food security over the past 25 years at multiple scales based on the latest long-term urban land time-series dataset and found that developing countries in Asia and Africa were
disproportionately affected by this process and required special attention. However, there are some limitations. First, we did not consider the specific crops cultivated (e.g. rice, wheat and maize) with each country when we estimate the grain production from the croplands occupied by urban expansion because the diversity and dynamics of crops cultivated in each country. Second, when we converted the cropland NPP to grain production, we did not consider the fallow cropland and may overestimate the grain production to some degree. Third, we did not consider the impact of other land use processes, such as converting cropland to forests or grassland and urban agriculture. In the future, the diversity of crops and the effects of land use policies should be considered to comprehensively examine the impacts of cropland displacement on food production and implications for global sustainability (Zeeza and Tasciotti 2010, van Vliet 2019).

6. Conclusions

The total cropland loss caused by global urban expansion was 1.59 × 10^{5} km², accounting for 45.9% of the total global urban expansion. Asia (82 880 km² or 52.1% of total loss) and China (42 190 km² or 26.5% of total loss) were the continent and country with the highest losses, respectively. The global urban expansion over cropland led to a total cropland NPP loss of 58.71 (56.52 ~ 59.81, 95% confidence interval) TgC. China, Brazil, USA, Argentina and India were the top five countries with the largest amounts of cropland NPP loss as a result of urban expansion. The sum of cropland NPP losses in these five countries accounted for approximately 65% of global loss.

Although the estimated grain production by global urban expansion accounted for only a small proportion (0.73%, or 0.70% ~ 0.74%) of the global grain production, it was sufficient to meet the minimum annual food intake demands of at least 36 million hungry individuals. Developing countries in Asia and Africa (e.g. China, Egypt and Vietnam) were disproportionately affected by this occupation process and particularly at risk. In these countries, urban expansion encroached fertile croplands, resulting in high grain production losses (1.32 ~ 1.55 times the global average). Therefore, it is imperative to restrict urban expansion over fertile cropland and encourage smart urban land growth to ensure that regional and global SDGs will be met.

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Data availability

The data that support the findings of this study are available upon request from the authors.

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