

The impact of global cropland changes on terrestrial ecosystem services value, 1992–2015

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Abstract: From 1992 to 2015, ecological environment has been threatened by the changes of cropland around the world. In order to evaluate the impact of cropland changes on ecosystem, we calculated the response of terrestrial ecosystem service values (TESVs) variation to cropland conversion based on land-use data from European Space Agency (ESA). The results showed that cropland changes were responsible for an absolute loss of \$166.82 billion, equivalent to 1.17% of global TESVs in 1992. Among the different regions, the impact of cropland changes on TESVs was significant in South America and Africa but not obvious in Oceania, Asia and Europe. Cropland expansion from tropical forest was the main reason for decreases in TESVs globally, especially in South America, Africa and Asia. The effect of wetland converted to cropland was notable in North America and Europe while grassland converted to cropland played an important role in Oceania, Africa and Asia. In Europe, the force of urban expansion cannot be ignored as well. The conversion of cropland to tropical or temperate forest partly compensated for the loss of TESVs globally, especially in Asia.

Keywords: terrestrial ecosystem services values (TESVs); cropland conversion; global

1 Introduction

Along with the growth of population and the development of economy, global cropland area continuing increased during 1992 to 2015 (FAOSTAT, 2017). However, although land is fixed, food is easily to shift from one country to another through global trade. Therefore, under the circumstance of globalization, the expansion of cropland was spatially imbalanced at a global level. During the process of global trade, the import-countries not only import

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goods, but also import various natural resources and ecological environment from export-countries. Higher-income countries tend to displace higher proportion of cropland abroad. In particular, Europe and Japan shift high pressure of ecosystems to lower-income countries (Weinzettel *et al.*, 2013). On the contrary, since 2000, foreign investors have contracted substantial land in Africa for crop planting (Schoneveld, 2017), which caused water risk in land acquisition area even with the most efficient irrigation implements (Johansson *et al.*, 2016). As a result, the spatial shift of cropland area would bring about a spatially imbalanced change in ecological environment. Plenty of environmental problems have emerged in cropland expansion areas, such as water and soil erosion (Tilman *et al.*, 2002), non-point pollution (Zhang *et al.*, 2004), water scarcity (Varis and Kummu, 2012), loss of biodiversity (Laurance *et al.*, 2014) and greenhouse gas emissions (Defries *et al.*, 2002).

On the other hand, rapid urbanization happened around the world as well. The percentage of population residing in urban areas increased by 11% during this period (UN, 2017). Usually, urban sprawl has negative impact on environment service values (ESVs) (Dupras and Alam, 2014; Cai *et al.*, 2017; Lu *et al.*, 2017). Cropland, particularly productive cropland (Tan *et al.*, 2005; Song *et al.*, 2015), is the most likely source of urban land. According to the projection of Bren d'Amour *et al.* (2017), urban expansion will bring about a 1.8%–2.4% reduction of global cropland by 2030. So, under the double pressure of cropland expansion and urban expansion, what did the ecological environment change correlated to cropland change? How to measure the changes? What was the regional difference of them? What were the specific reasons of terrestrial ecosystem service values (TESVs) loss in different regions? These questions are what we cared about.

Various ecological issues have aroused more and more public concerns. People began to attach importance to the goods and services provided by natural ecosystems. To evaluate the worth of ecosystem services, researchers calculated and estimated the economic value of them (Costanza *et al.*, 1997; de Groot *et al.*, 2012; Xie *et al.*, 2017). In this way, the ecosystem services can be described quantitatively. The most significant contribution of ESVs is that it reminds people to treat natural assets as important components of wealth, well-being and sustainability (Costanza *et al.*, 2014). Based on this recognition, Li and Fang (2014) overlaid ESVs map and GDP map at global scale to produce a synthetic green GDP.

Many studies focused on the impact of land-use change on ESVs at regional scale (Fu *et al.*, 2016; Quintas-Soriano *et al.*, 2016), while global-scale estimates were relatively rare (Song, 2018). Among different land cover changes, forest change on ESVs usually attracted more attention (Sheng *et al.*, 2017). However, cropland is the foundation of food production which is greatly affected by human activities all over the world (Shi *et al.*, 2016). In fact, the most important form of land conversion during the past decades was cropland expansion based on previous research (Lambin and Meyfroidt, 2011). As a result, cropland played an important role in ESVs variation around the world. For example, the reclamation of cropland accounted for the largest loss in ESV in China from 1988 to 2008 (Song and Deng, 2017). In this case, it is essential to estimate the impact of cropland changes on ESVs at global scale with a relatively consistent dataset. Given that the proportion of marine ecosystems is too large at global level, this article only focused on TESVs.

2 Materials and methodology

2.1 Data sources

The land-use maps in this study were derived from the latest land cover classification dataset products of European Space Agency (ESA), including annual data between 1992 and 2015 with a resolution of 300 m (ESA, 2017). The relatively consistency of the dataset guarantees that the data are comparable among years. Besides that, we used the framework established by Costanza *et al.* (1997), which has been widely used all over the world in assessing the TESVs of different land cover types.

2.2 Calculation of TESVs

According to the assessment model proposed by Costanza *et al.* (1997), the biosphere was divided into 16 ecosystems and 17 services types. Combined with land-use maps, we grouped the ecosystems into seven types: cropland, tropical forest, temperate/boreal forest, grassland, wetland, bare land and urban areas. Wetland owns the highest value among the seven types, followed by tropical forest, temperate forest, grassland and cropland. In this assessment model, bare land and urban areas have no value (Table 1). The total value of terrestrial ecosystems can be calculated as:

Table 1 TESVs per unit area (\$/ha per year based on the 2016 value of the USD) (after Costanza *et al.*, 1997)

| Ecosystem services | Tropical forest | Temperate forest | Grassland | Cropland | Wetland |
|------------------------|-----------------|------------------|-----------|----------|----------|
| Gas regulation | 0.00 | 0.00 | 11.34 | 0.00 | 215.46 |
| Climate regulation | 361.26 | 142.56 | 0.00 | 0.00 | 0.00 |
| Disturbance regulation | 8.10 | 0.00 | 0.00 | 0.00 | 7353.18 |
| Water regulation | 9.72 | 0.00 | 4.86 | 0.00 | 24.30 |
| Water supply | 12.96 | 0.00 | 0.00 | 0.00 | 6156.00 |
| Erosion control | 396.90 | 0.00 | 46.98 | 0.00 | 0.00 |
| Soil formation | 16.20 | 16.20 | 1.62 | 0.00 | 0.00 |
| Nutrient cycling | 1493.64 | 0.00 | 0.00 | 0.00 | 0.00 |
| Waste treatment | 140.94 | 140.94 | 140.94 | 0.00 | 6766.74 |
| Pollination | 0.00 | 0.00 | 40.50 | 22.68 | 0.00 |
| Biological control | 0.00 | 6.48 | 37.26 | 38.88 | 0.00 |
| Habitat/Refugia | 0.00 | 0.00 | 0.00 | 0.00 | 492.48 |
| Food production | 51.84 | 81.00 | 108.54 | 87.48 | 414.72 |
| Raw materials | 510.30 | 40.50 | 0.00 | 0.00 | 171.72 |
| Genetic resources | 66.42 | 0.00 | 0.00 | 0.00 | 0.00 |
| Recreation | 181.44 | 58.32 | 3.24 | 0.00 | 929.88 |
| Cultural | 3.24 | 3.24 | 0.00 | 0.00 | 1427.22 |
| Total | 3251.00 | 489.00 | 376.00 | 149.00 | 23952.00 |

$$TESV = \sum A_i \times V_i \tag{1}$$

where A_i is the total area of ecosystem i and V_i is the monetary value of ecosystem i . So, the change caused by cropland ecosystems can be written as:

$$\Delta TESV_c = \Sigma A_{c-i} \times (V_c - V_i) + \Sigma A_{i-c} \times (V_i - V_c) \quad (2)$$

where A_{c-i} represents the loss area of cropland converted to ecosystem i between 1992 and 2015, while A_{i-c} represents the gain area of cropland converted from ecosystem i during the study period. V_c is the monetary value of cropland. The change rates between 1992 and 2015 are:

$$R_1 = \frac{\Delta TESV_c}{\Sigma A_{c-i} \times V_c + \Sigma A_{i-c} \times V_i} \quad (3)$$

$$R_2 = \frac{\Delta TESV_c}{\Sigma A_{i1992} \times V_i} \quad (4)$$

R_1 shows the impact of cropland conversion on TESVs of changing areas correlated to cropland while R_2 represents the impact of cropland compared to total TESVs of 1992.

3 Results and discussion

3.1 Cropland change

During 1992 to 2015, new cropland was largely distributed at the edge of Amazon forest, Eurasian steppe and Sahara Desert (Figure 1). The main sources of it were tropical forest and grassland, accounting for 41.03% and 38.13%, respectively. Cropland converted from forest was mostly located in South America, Southeast Asia, Europe and Sub-Saharan Africa. Around the Central Asia, North Africa and Southeast Australia, cropland usually converted from grassland.

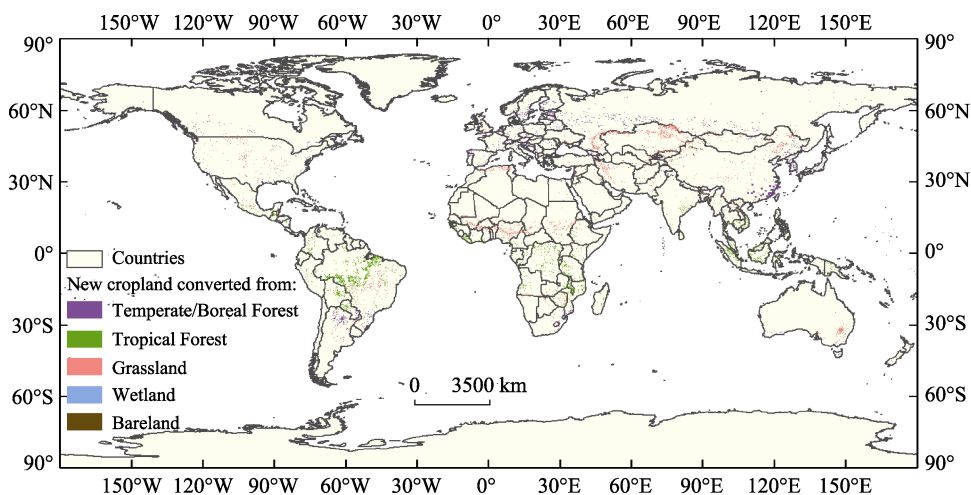


Figure 1 Cropland gains between 1992 and 2015

The underlying factors driving changes in cropland can be summarized as either natural or human-induced. Over long time scales, the effects of natural factors are more pronounced. Researchers found that cropland have expanded in higher latitude or altitude regions as a result of global warming during the past decades (Iizumi and Ramankutty, 2015), such as the expansion of cropping boundary in Northeast China (Piao *et al.*, 2010).

On the other hand, human-induced factors exert a more significant impact on cropland

changes over shorter time scales, which can be found through 24 years of ESA data. According to previous research, the expansion of Amazon forest, Sub-Sahara Desert, Southeast Asia and Central Asia was closely related to increasing foreign investment and inherent suitability for large-scale management (Schoneveld, 2014; Antonelli *et al.*, 2015; Swinnen *et al.*, 2017). Rapid expansion of cropland in the southeastern Amazon forest, for example, was mainly related to the global trade in soybeans; this crop alone was responsible for a 33.8% reduction in forested area between 1988 and 2015 (Damien *et al.*, 2017). The rapid cropland expansion seen in Indonesia and Malaysia may be related to the production of biofuels like oil palm (Tscharncke *et al.*, 2012).

As for cropland decreasing area, the demise of communism in the former Soviet Union resulted in the widespread abandonment of cropland in Eastern Europe during the 1990s (Smaliychuk *et al.*, 2016). Besides that, urban growth, as a result of economic development, often occurs at the expense of croplands, especially high-yield cultivated areas (Vliet *et al.*, 2017). This situation was concentrated in Europe, East Asia and North America during 1992 to 2015 (Figure 2). In addition, some countries adopted a series of policies aimed at encouraging farmers to let their land lie fallow or to convert it to forests or grasslands, which also caused a decrease of cropland. Examples include Grain for Green program in China, the Conservation Reserve Program in the United States, and the land fallow and crop production system that has been implemented in the European Union.

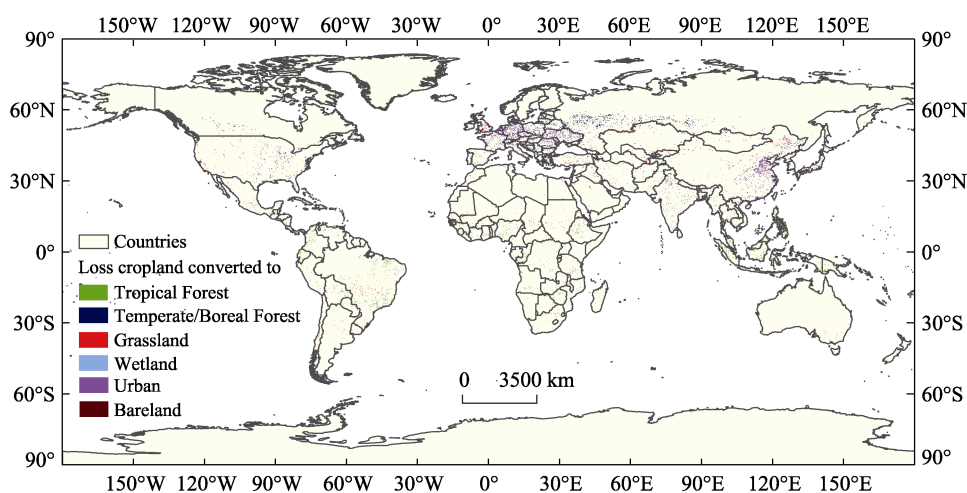


Figure 2 Cropland loss between 1992 and 2015

3.2 Changes in TESVs at global level

The total global TESVs of 1992 were \$14.27 trillion. Asia took up 31.64% of the global TESVs, ranking the first place, followed by South America and Africa, accounting for 25.49% and 23.46% respectively. A reduction of TESVs caused by cropland conversion was \$166.82 billion, equaled to 1.17% of the total TESVs in 1992. In the changing areas correlated to cropland, the TESVs decreased by 65.21% globally. From the detailed calculation, it can be seen that conversion of tropical forest to cropland is the main reason for the decrease of TESVs (Table 2), up to \$187.47 billion, which exceeded the net reduction caused by cropland conversion. Previous studies have also shown that tropical forests were the primary

sources of new cropland in the 1980s and 1990s, which were mainly distributed in South America, Sub-Saharan Africa, and Southeast Asia (Gibbs *et al.*, 2010). Among the 17 ecosystem services, the ESVs of nutrient cycling decreased largely (\$63.94 billion). Only the ESVs of biological control increased a little, about \$1.37 billion.

Table 2 Changes in TESVs caused by cropland changes at a global level, 1992–2015

| 1992 | 2015 | V (\$/ha) | A ($\times 10^6$ ha) | TESVs ($\times 10^9$ \$) |
|-------------------------|-------------------------|-----------|-----------------------|---------------------------|
| Cropland converted into | Tropical forest | 3102.00 | 17.62 | 54.67 |
| | Temperate forest | 340.00 | 12.43 | 4.23 |
| | Grassland | 227.00 | 6.77 | 1.54 |
| | Wetland | 23803.00 | 0.05 | 1.12 |
| | Urban | −149.00 | 25.02 | −3.73 |
| | Bare land | −149.00 | 0.64 | −0.09 |
| Tropical forest | Converted into cropland | −3102.00 | 60.44 | −187.47 |
| Temperate forest | | −340.00 | 25.96 | −8.83 |
| Grassland | | −227.00 | 56.17 | −12.75 |
| Wetland | | −23803.00 | 0.68 | −16.12 |
| Bare land | | 149.00 | 4.07 | 0.61 |

3.3 Changes of TESVs at regional level

With the same method, we calculated the changes of TESVs caused by cropland changes in different regions (Table 3).

Table 3 Changes in TESVs caused by cropland changes at regional level, 1992–2015

| Region | TESVs of 1992 ($\times 10^9$ \$) | Growth rate of cropland area (%) | TESVs gains caused by cropland loss ($\times 10^9$ \$) | TESVs loss caused by cropland gains ($\times 10^9$ \$) | TESVs ($\times 10^9$ \$) | R ₁ (%) | R ₂ (%) | Main Reason |
|---------------|-----------------------------------|----------------------------------|---|---|---------------------------|--------------------|--------------------|-------------|
| Global | 14269.62 | 3.96 | 57.73 | 224.56 | −166.83 | −65.21 | −1.17 | A |
| North America | 1624.14 | 1.31 | 2.44 | 18.93 | −16.48 | −78.72 | −1.01 | B |
| South America | 3622.39 | 12.02 | 19.85 | 101.50 | −81.65 | −74.74 | −2.25 | A |
| Africa | 3334.06 | 7.52 | 9.04 | 51.99 | −42.95 | −73.92 | −1.29 | A |
| Europe | 548.15 | −0.67 | 0.12 | 3.33 | −3.21 | −54.57 | −0.59 | C |
| Asia | 4496.71 | 2.34 | 25.86 | 47.58 | −21.72 | −36.46 | −0.48 | A |
| Oceania | 587.69 | 4.26 | 0.38 | 1.01 | −0.63 | −36.26 | −0.11 | D |

Notes: A stands for the main reason of decreasing TESVs, which was cropland converted from tropical forest. Similarly, B stands for cropland converted from wetland; C stands for cropland converted from temperate forest and D stands for cropland converted from grassland.

Among the six continents, the most significant change of TESVs happened in South America where the changing value was tantamount to 2.25% of the total TESVs of South America in 1992. Meanwhile, the growth rate of cropland area in South America was 12.02%, also ranking the first place among the six continents. In the cropland conversion area, the TESVs decreased sharply by 74.74%. In possession of “the lung of the earth”, South America took up nearly a quarter of the total TESVs. However, a reduction of \$81.65

billion caused by cropland change between 1992 and 2015 almost accounted for half of the total global TESVs variation during the period, suggesting a severe situation of ecological destruction in South America. The main reason for the reduction was the loss of tropical forest, especially at the edge of Amazon forest (Figure 3). Previous researches have paid much attention to the deforestation of Amazon during the past decades (Brown *et al.*, 2016). The phenomenon of TESVs loss caused by cropland change was greatly significant in Brazil, tantamount to 3.62% of the total value of Brazil in 1992, which was mainly caused by soybean cultivation. However, researchers found that in most areas, the value of original ecosystem services exceeded the value of soybean rents (Mann *et al.*, 2012).

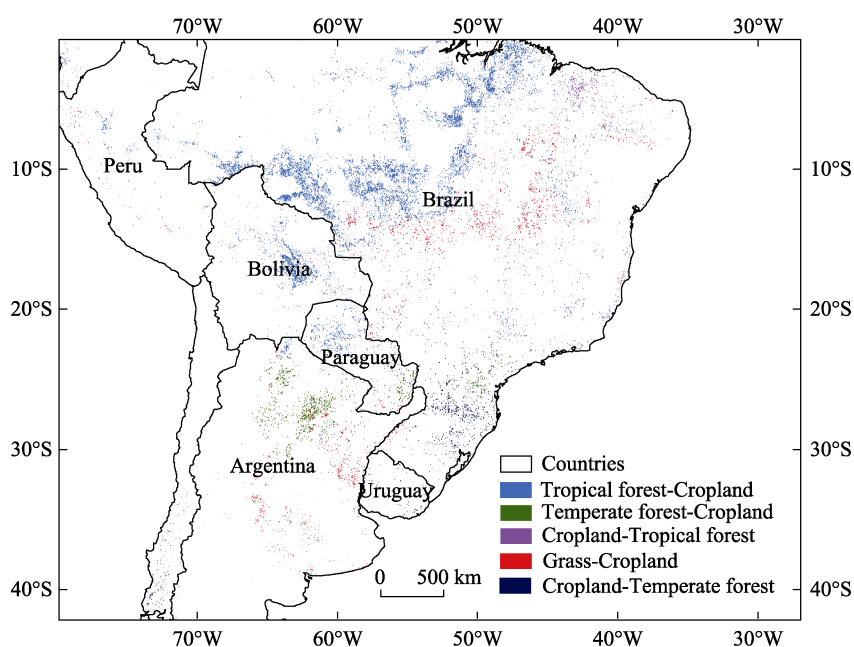


Figure 3 Cropland change in South America, 1992–2015 (Tropical forest-Cropland means that tropical forest in 1992 was converted into cropland in 2015. Other conversions are similar to this.)

Along with the rapid expansion of cropland in Africa, there was also a substantial decrease of TESVs, equaling to 1.29% of the TESVs of Africa in 1992, occupying nearly a quarter of the total TESVs reduction around the world caused by cropland change. Quantity of tropical forest was destroyed, converting to cropland in this region. Besides this, the loss of grassland also had an evident impact on the loss of TESVs in Africa, particularly at the south edge of the Sahara Desert (Figure 4). The loss of TESVs was serious in many African countries like Algeria, Malawi and Liberia. Among the top 10 TESVs loss countries due to cropland change around the world, African countries took half of the seats (Figure 5). Niquisse and Cabral (2017) found that the ESVs of Mozambique decreased by 11.4% between 2005 and 2009 while the cropland biome increased considerably during this period. Nowadays, land grabbing in Africa has become more and more widespread (Conigliani *et al.*, 2018). According to the projection of Kubiszewski *et al.* (2017), ESVs will decrease most sharply in Africa by 2050 under the scenario of market forces.

In North America, larger area of wetland was converted to cropland compared to other continents, which brought about an obvious decrease of TESVs in the changing areas.

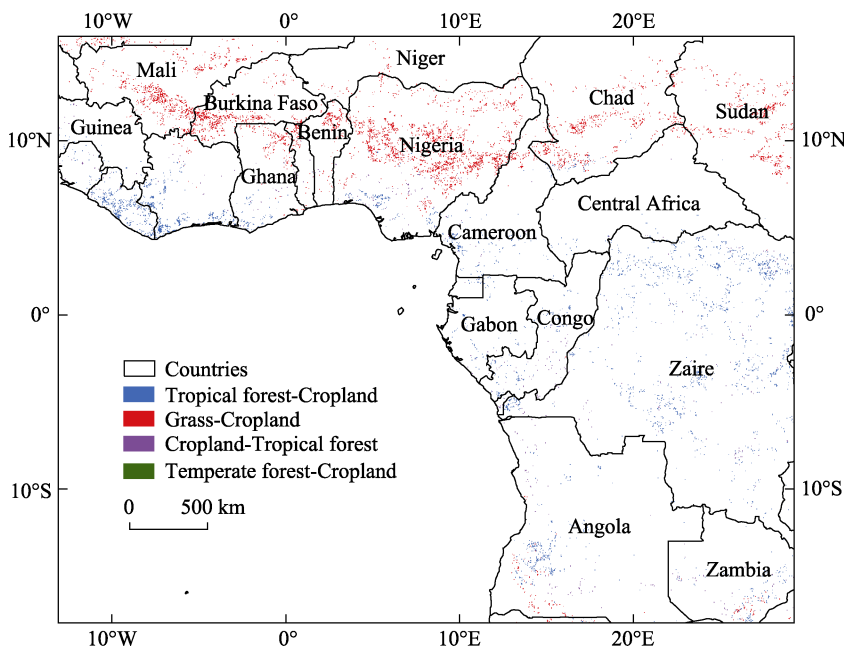


Figure 4 Cropland change in Africa, 1992–2015

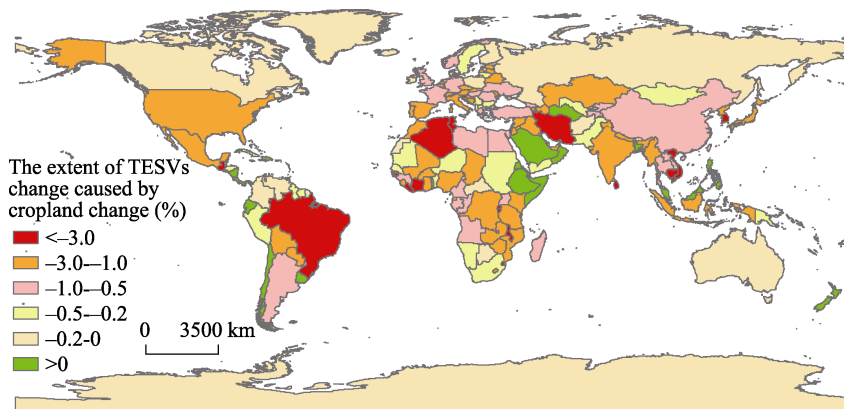


Figure 5 The extent of TESVs changes caused by cropland change (R_2), 1992–2015

Most of the lost wetlands are distributed along the Atlantic and Gulf coasts, called estuarine wetland. As stated in the review by U.S. Fish & Wildlife Service, the area of estuarine wetland continuously decreased from the 1950s to the 1990s. Between 1986 and 1997, nearly a quarter of the wetland was converted to cropland (Dahl, 2000).

Although the area of cropland decreased in Europe between 1992 and 2015, the conversion of cropland still led to a decrease in TESVs, tantamount to 0.59% of the TESVs of Europe in 1992. Unlike other regions, 67% of the lost cropland converted to urban areas, deteriorating the ecological environment. Certainly, the conversion of cropland to temperate forest contributed to the major decrease of TESVs. However, the obvious difference between TESVs change caused by cropland gains and loss suggested that the effect of urban expansion in Europe cannot be ignored as well. Except from temperate forest loss and urban ex-

pansion, wetland converted to cropland also took a place in the reduction of TESVs in Europe. In the Hungarian Plain, 30% of croplands lie on former wetland (Pinke *et al.*, 2018).

The increase of TESVs caused by cropland loss was evident in Asia, taking up 44.79% of the global gains. As a result, the net decrease of TESVs was relatively small in Asia in spite of a not small growth rate of cropland expansion and the largest TESVs proportion in 1992, only equivalent to 0.48% of original TESVs. Large area of forest was converted from cropland during the period, which may have a relationship with environmental conservation policies in East Asia and the forest transition in Southeast Asia. The loss of grassland to cropland had an impact on the decrease of TESVs as well in Asia, especially at the edge of Eurasian Steppe.

The least change of TESVs was happened in Oceania where the main source of new cropland was grassland, taking up 80.63%. The unit value of cropland and grassland was relatively similar. As a result, TESVs caused by cropland change only equaled to 0.11% of the total value in 1992.

3.4 Uncertainties of the method

The assessment of ESV proposed by Costanza *et al.* in 1997 raised public concerns of environmental protection and started a boom in this topic research. However, the assessment overestimated the value of wetland and underestimated the value of cropland, which has been criticized in previous research (Xie *et al.*, 2003). Besides, some researchers also showed concerns of limitations and constrains of benefit transfer method which is the foundation of the assessment (Johnston and Rosenberger, 2010).

4 Conclusions

Referred to the ESVs per unit area defined by Costanza *et al.* (1997), we focused on the impact of cropland changes on global TESVs between 1992 and 2015. With the help of land-use data from ESA, we obtained three main conclusions:

(1) The reduction of TESVs caused by cropland conversion was \$166.82 billion, tantamount to 1.17% of global TESVs in 1992. The major loss was happened in new cropland region converted from tropical forest.

(2) The TESVs of South America took up nearly a quarter of global value, but the reduction of TESVs caused by cropland change made up almost half of the global value, equivalent to 2.25% of total TESVs of South America in 1992. Except from South America, the impact of cropland changes on TESVs was significant in Africa but not obvious in Oceania, Asia and Europe.

(3) Cropland expansion from tropical forest was the main reason for the decrease of TESVs in South America, Africa and Asia. Beyond that, the effect of wetland to cropland was notable in TESVs reduction in North America and Europe. Grassland converted to cropland played an important role in the diminution of TESVs in Oceania, Africa and Asia. In Europe, the force of urban expansion cannot be ignored as well. The conversion of cropland to tropical or temperate forest partly compensated for the loss of TESVs globally, especially in Asia.

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