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Telecoupled land-use changes in distant countries

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Abstract
International food trade has become a key driving force of agricultural land-use changes in trading countries, which has influenced food production and the global environment. Researchers have studied agricultural land-use changes and related environmental issues across multi-trading countries together, but most studies rely on statistic data without spatial attributes. However, agricultural land-use changes are spatially heterogeneous. Uncovering spatial attributes can reveal more critical information that is of scientific significance and has policy implications for enhancing food security and protecting the environment. Based on an integrated framework of telecoupling (socioeconomic and environmental interactions over distances), we studied spatial attributes of soybean land changes within and among trading countries at the same time. Three distant countries — Brazil, China, and the United States — constitute an excellent example of telecoupled systems through the process of soybean trade. Our results presented the spatial distribution of soybean land changes — highlighting the hotspots of soybean gain and soybean loss, and indicated these changes were spatially clustered, different across multi-spatial scales, and varied among the trading countries. Assisted by the results, global challenges like food security and biodiversity loss within and among trading countries can be targeted and managed efficiently. Our work provides simultaneously spatial information for understanding agricultural land-use changes caused by international food trade globally, highlights the needs of coordination among trading countries, and promotes global sustainability.

Keywords: agricultural land-use changes, soybeans, spatial attributes, telecoupling, moving window analysis

1. Introduction

Agricultural land-use changes brought on by international food trade have had great influence on global food production and the environment (Parry *et al*. 2005; DeFries *et al*. 2010; Lenzen *et al*. 2012). Noting the importance of distant interactions among trading countries, researchers have studied agricultural land-use changes caused by international food trade among multiple trading countries together (Adger *et al*. 2009; Liu *et al*. 2013; Lathuilliere *et al*. 2014). These studies heavily rely on statistics data without spatial attributes. However, land use changes, including agricultural land-use changes, are not spatially uniform and embody important information, which need to be investigated (Zaccarelli *et al*. 2008; Fahrig *et al*. 2011; Sun *et al*. 2015a). Questions regarding spatial attributes of agricultural land-use changes include where the changes occur, whether they occur clustered or evenly, if they differ at multiple scales, and whether they vary among trading countries. The answers will help understand the dynamics

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of food production and environmental problems within and among trading countries, which provide scientific information and policy implications for enhancing food security and protecting environment globally.

To answer these questions, we place our study under an integrated framework of telecoupling (socioeconomic and environmental interactions over distances). The telecoupling framework is composed of five interrelated components: systems, agents, flows, causes, and effects. Systems are coupled human and natural systems (Liu *et al*. 2007), which can be further classified as sending, receiving, and spillover systems. Agents are decision-making entities involved in the telecoupling, and they affect flows of energy, materials, and information between the systems. Causes are drivers or factors that generate the telecoupling and alter its dynamics, resulting in socioeconomic and environmental effects. The telecoupling framework has been applied to analyze a number of important issues such as ecosystem services (Liu and Yang 2013; Liu *et al*. 2016), food and forest sustainability (Liu 2014), conservation (Gasparri and Waroux 2015; Liu *et al*. 2015a), energy sustainability (Liu *et al*. 2015b; Fang *et al*. 2016), water (Deines *et al*. 2016), and species invasion. These applications have helped identify critical research gaps and hidden linkages within and among different geographic regions and across multi-spatial scales, and thus the telecoupling framework is adequate to address our aim here. In this paper, we focus on the effects of telecoupling *via* international food trade on agricultural land-use changes.

We use soybeans, one of the top traded commodities, as an example to investigate the spatial attributes of agricultural land-use changes within and among trading countries. International soybean trade began to soar after the implementation of genetically modified (GM) technique in 1996 (Brookes and Barfoot 2005), which has significantly promoted soybean expansion *via* simplifying crop cultivation (Bonny 2011). China used to be the largest soybean producer and exporter, but has become the largest soybean importer. Due to the advanced agricultural technology and management in main exporting countries, imported soybeans are much cheaper than domestic ones in China (Zhao *et al*. 2012). To become a World Trade Organization (WTO) member, China reduced the tariff on imported soybeans from 130 to 3% in 1995 (Wang 2000). Since then, large amounts of cheap soybeans have been poured into the country, causing a substantial decline of soybean lands — significantly beginning in 2009 (NBSC 2015). In 2014, China imported 61% of the world's total exported soybeans, most of which were from the United States and Brazil (ASA 2015; NBSC 2015). The United States is the world's largest soybean producer and exporter, and its soybean lands and production have been increasing in the past several decades. The United States is also the largest soybean supplier of China. For example, one-quarter of its production was exported to China in 2014 (ASA 2015). Although the amount of soybeans exported from the United States to China is still increasing, the increasing pace has been slowed down due to the competition from Brazil (Casey 2012). Moreover, for the imported soybeans in China, the proportion of the United States has decreased from 82% in 1995 to 45% in 2014, while Brazilian proportion has increased from 3.4 to 40% during the same period (ASA 2015; CGAC 2015; NBSC 2015). Brazil is now the second largest soybean supplier of China. One-third of its soybean production was exported to China in 2014 (Salin and Ladd 2015). As the second largest soybean producer and exporter, Brazil is facing the challenge of deforestation caused by the expansion of soybean lands (Morton *et al*. 2006). To conserve the Amazon rainforest, the Soy Moratorium (an agreement that forbids major soybean traders to purchase soybeans grown on lands cleared after July 2006 in the Brazilian Amazon) was enforced in 2006 (Gibbs *et al*. 2015), which has effectively curbed the illegal soybean expansion and soybean lands in some areas even experienced a decreasing trend (Gusso *et al*. 2014). Nonetheless, its national soybean production continues to increase, mainly due to the agricultural intensification, i.e., improvement of per unit of land yield (Lambin and Meyfroidt 2011).

Through the process of international soybean trade, China, Brazil and the United States constitute a telecoupled system. We consider China as the receiving system (importing soybeans), Brazil as the sending system (exporting soybeans), and the United States as the spillover system (its traditional soybean trade with China has been negatively affected by Brazil). We then choose Heilongjiang Province in China, the State of Mato Grosso (MT) in Brazil, and Western Corn Belt (WCB) in the United States as our case (Fig. 1), because they are the top soybean production region in each country — reflecting national soybean dynamics, and are significantly connected and affected with each other by the soybean trade (ASA 2015; NBSC 2015; Salin and Ladd 2015). Outcompeted by the imported soybeans, soybean lands in Heilongjiang have been declining since 2009 (Ma 2009; NBSC 2015). China's share of MT's exported soybeans has been increasing rapidly, reaching 64% in 2014 (Salin and Ladd 2015). WCB encompasses seven states — North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa and Missouri. Unlike the Eastern Corn Belt, a substantial proportion of the soybeans produced in WCB is China exported oriented (Newton and Kuethe 2015). During 2005 and 2010, soybean lands dramatically decreased from 4.4 to 2.9 million ha in Heilongjiang (Huang *et al*. 2013), slightly decreased from 6.2 to 6.1 million ha in MT (Gusso *et al*. 2014), and slightly increased from 15.3 to

15.6 million ha in WCB (Boryan *et al*. 2011). The simultaneous understanding about spatial attributes of soybean land changes in these regions is still unclear. Here, we studied their spatial attributes at the same time, including where the soybean land changes occurred, whether they occurred clustered or evenly, if they were different at multiple scales, and if they varied among three regions, using soybean maps of 2005 and 2010.

2. Materials and methods

Soybean maps of 2005 and 2010 were the key input. Soybean map of Heilongjiang was created by moderate resolution imaging spectroradiometer (MODIS) data and provided at 250-m spatial resolution (Huang *et al*. 2013). Soybean map of MT was also produced by MODIS data using MODIS crop detection algorithm (Gusso *et al*. 2014) and provided at 250-m spatial resolution. Soybean map of WCB was prepared by the National Agricultural Statistics Service at the United States Department of Agriculture (Boryan *et al*. 2011). The data for South Dakota, Kansas, Minnesota, and Missouri were not available in 2005, so we used 2006 WCB data as an approximation of 2005. Because WCB data were originally produced at 56-m in 2006 and 30-m in 2010, we resampled both to 250-m to keep consistent with the data of Heilongjiang and MT.

To measure the spatial attributes of soybean land changes, we adopted a change detection analysis to map the soybean changes at the pixel level between 2005 and 2010 in Heilongjiang, MT and WCB, respectively. To examine whether the agricultural land changes had encroached the areas that harbor rich biodiversity, we superimposed the terrestrial ecoregion defined by WWF on the results of change detection (Olson *et al*. 2001). Next, we applied a moving window analysis to the results of change detection, including soybean gain and soybean loss, to detect the change information across multi-spatial scales by varying window size. Window kernel was used to calculate the proportion of soybean gain and soybean loss in a series of pre-defined windows. The window sizes varied from 7×7 pixels (3.1 km^2), 27×27 pixels (45.6 km^2), 81×81 (410.1 km^2), which covered three orders of magnitude and can ensure a precise measurement of the multi-spatial scales information (Sun *et al*. 2015b).

3. Results

3.1. Soybean land changes in space

Spatial attributes of soybean land changes were complex within Heilongjiang, MT, and WCB and significantly different among the three regions (Figs. 2–4). Although soybean land changes were extensive in Heilongjiang, their spatial distribution and intensity were very heterogeneous (Fig. 2). Hotspots of soybean gain mainly occurred in the east, while hotspots of soybean loss were more widespread and

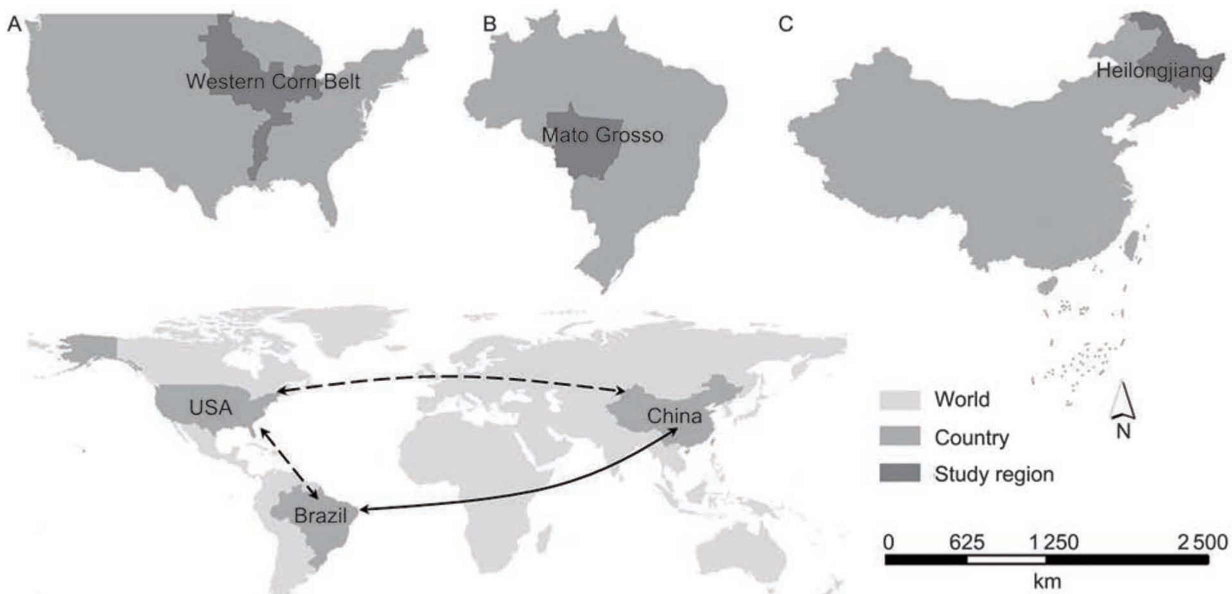

Fig. 1 Map of study regions. A, Western Corn Belt (WCB) in the United States (Alaska and Hawaii are not shown). B, State of Mato Grosso (MT) in Brazil. C, Heilongjiang Province in China. The insert world map is a simplified illustration showing the telecoupling relationship among the three countries, where China is the receiving system, Brazil is the sending system, and the USA is the spillover system. Arrows indicate directions of flows of soybeans and money, which are bidirectional here. Solid arrow is direct flow between Brazil and China, and dashed arrows are indirect flow between Brazil and China by passing through the USA, refer to Liu *et al*. (2013) for more information.

intensive in both west and east parts. In MT, hotspots of soybean gain and soybean loss concentrated in the middle and southeast part (Fig. 3). In particular, the spatial patterns of soybean land changes, soybean gain and soybean loss, were similar and spatially close. In WCB, soybean land changes distributed in the middle and east parts without significant hotspots and the spatial patterns of soybean gain and soybean loss were also similar and adjacent (Fig. 4). Moreover, the superimposed ecoregions in Figs. 2–4 indicated that both Heilongjiang and MT had a large amount of soybean land changes occurred within the ecoregions, including the Mongolian steppe in east Heilongjiang, and Cerrado woodlands and savannas in middle and southeast MT. Nonetheless, we found some areas of soybean gain were outside the ecoregion Cerrado woodlands and savannas in the middle MT, though soybean loss was still inside the ecoregion. Most changed soybean lands in WCB were outside the ecoregion with a few areas overlapped with the

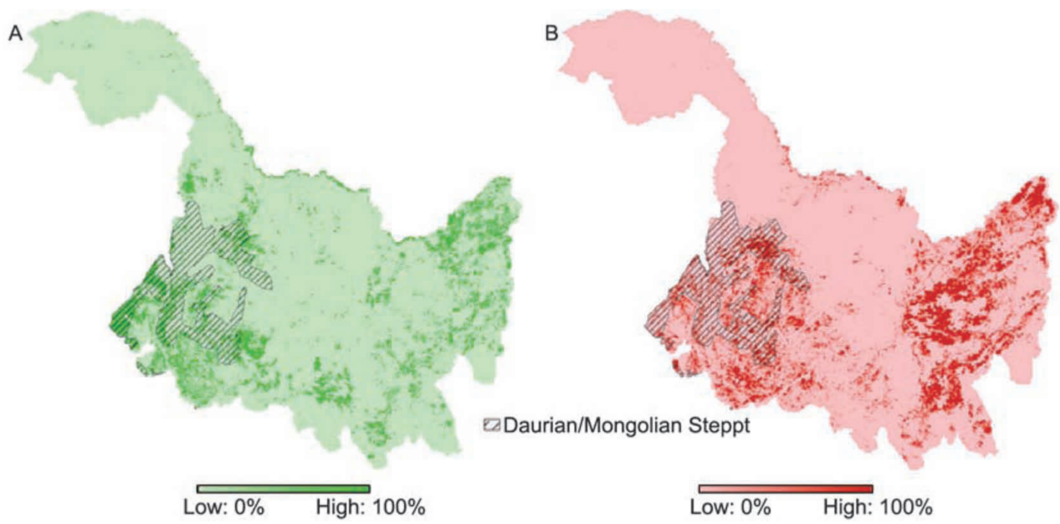

Fig. 2 Map showing the results of change detection in Heilongjiang. A, soybean gain. B, soybean loss. Legend bars indicate soybean change rate from light color (low: 0%) to dark color (high: 100%). To improve visibility and be more informative, pixel-level results are normalized by using a spatial smoothing technique (refer to Sun *et al*. 2015a for detail). Terrestrial Ecoregion was superimposed on the result to indicate hotspots of biodiversity conservation (Olson *et al*. 2001). The same processing information also applies to Figs. 3 and 4.

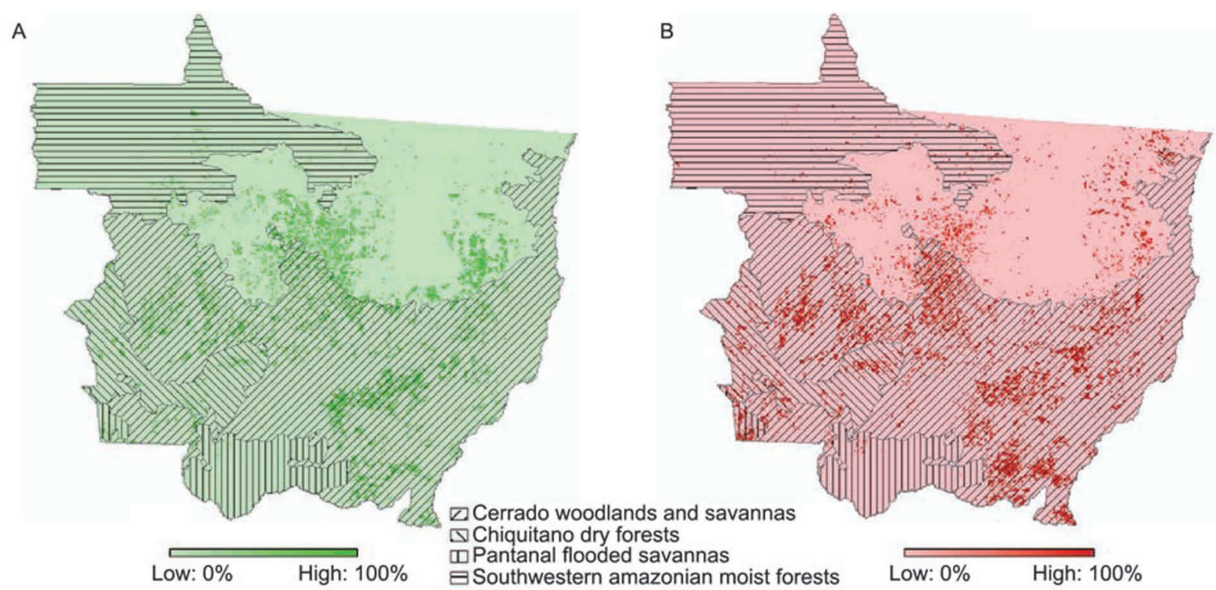

Fig. 3 Map showing the results of change detection in MT. A, soybean gain. B, soybean loss.

northern prairies.

3.2. Soybean land changes across multi-spatial scales

Soybean land changes behaved differently across multi-spatial scales and among Heilongjiang, MT, and WCB (Figs. 5–7). The profiles displayed the relation of soybean gain area (blue circles) and loss area (red circles) with their respective soybean area density. The profiles in all sub-figures were skewed to the left, but tailed to the right, indicating more soybean land changes occurred at low- and intermediate-density soybean lands than highly dense soybean lands. In Heilongjiang, the profile of soybean loss was higher than that of soybean gain in all three windows, which indicated an overall decrease of soybean lands across multi-spatial scales (Fig. 5). In particular, the gap between the loss profile and gain profile became gradually large from 7×7 window to 81×81 window in Heilongjiang, showing more soybean loss at the large scale. In MT, the profiles of soybean loss and soybean gain were almost overlapped, which showed total soybean lands are relatively stable, i.e., offset by similar gain and loss (Fig. 6). However, there was a small amount of low-density soybean loss, because the profile of soybean loss was higher than the profile of soybean gain along the left part of the horizontal axis, i.e., low-density soybean lands. In WCB, we found the profiles of 27×27 window and 81×81 window had a hump along intermediately dense soybean lands, where the profile of soybean gain was higher than that of soybean loss, indicating a slight increase of intermediate-density soybean lands in WCB at middle and large scales (Fig. 7). Additionally, comparing the profile length of three regions, the profiles of Heilongjiang (both soybean loss and soybean gain) of three scales were the longest, showing that soybean lands were more continuous in Heilongjiang than that of MT and WCB.

4. Discussion

By adding spatial attributes, our analysis shows more important, intensive, and complex agricultural land changes brought on by international food trade, which provides simultaneous information for better understanding telecoupled effects and coping with global challenges like food production and environmental conservation. We have mapped the distribution of soybean land changes in three major soybean production regions in China, Brazil, and the United States at the same time, highlighting the soybean gain and soybean loss, and indicated these changes were spatially clustered, different across multi-spatial scales, and varied among trading partners. In Heilongjiang, the spatial distributions of soybean land changes show that soybean loss was more widespread and intensive than soybean gain. Nonetheless, it also shows hotspots of soybean gain in west Heilongjiang, because of weather disturbance, farmers had to grow soybeans, which are a major alternative in a snowy spring like 2010 (Sun *et al*. 2015a), and other factors like fluctuation of crop market, crop rotation, cultivation tradition, and government policies. In MT, soybean loss and soybean

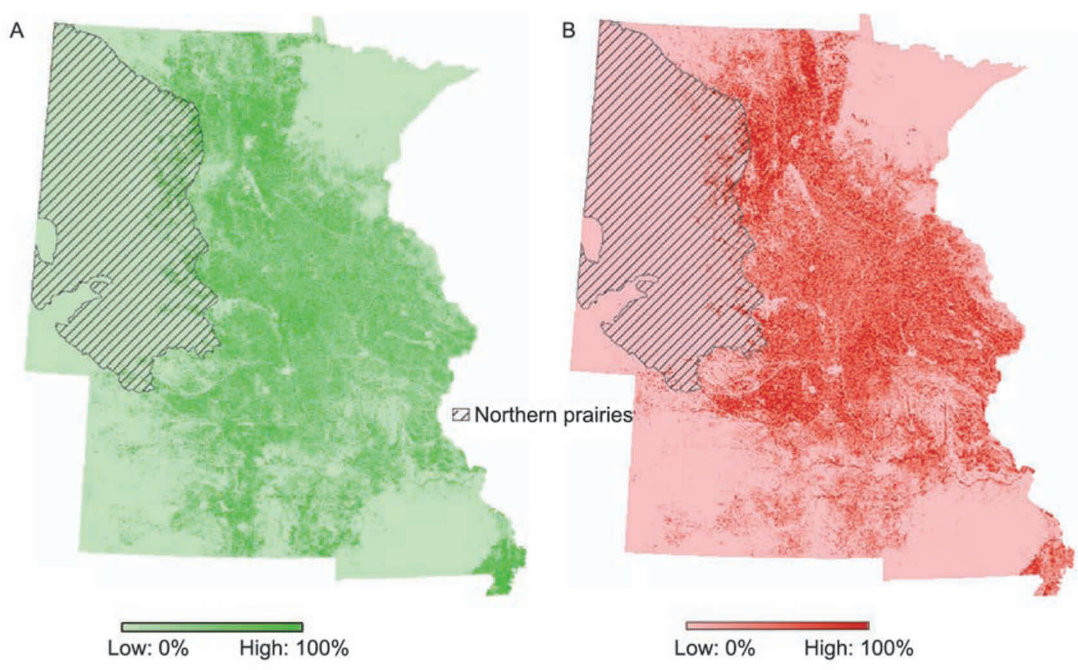

Fig. 4 Map showing the results of change detection in WCB. A, soybean gain. B, soybean loss.

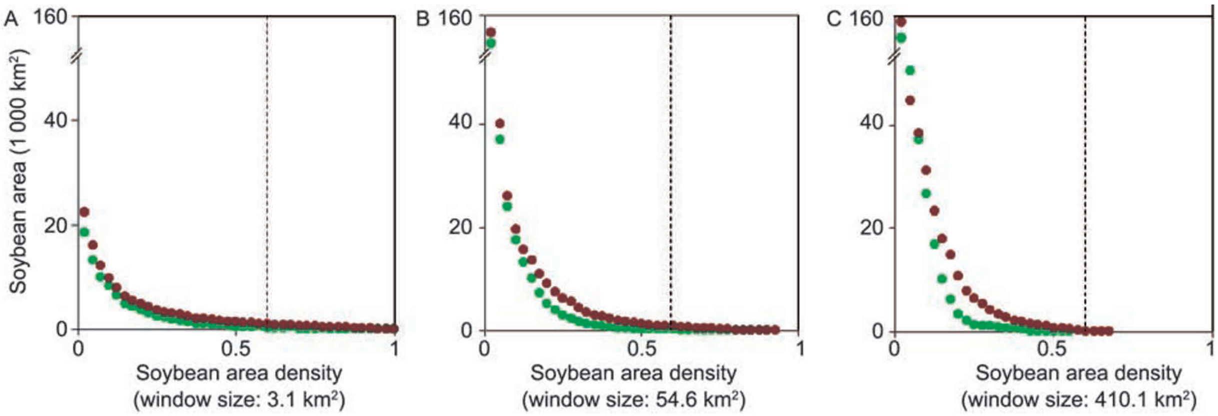

Fig. 5 Soybean area loss (red circles) and soybean area gain (green circles) in relations to their soybean area density for selected widow sizes in Heilongjiang. The vertical dashed line, soybean area density=0.6, in each sub-figure was superimposed to assist analysis. The same as below.

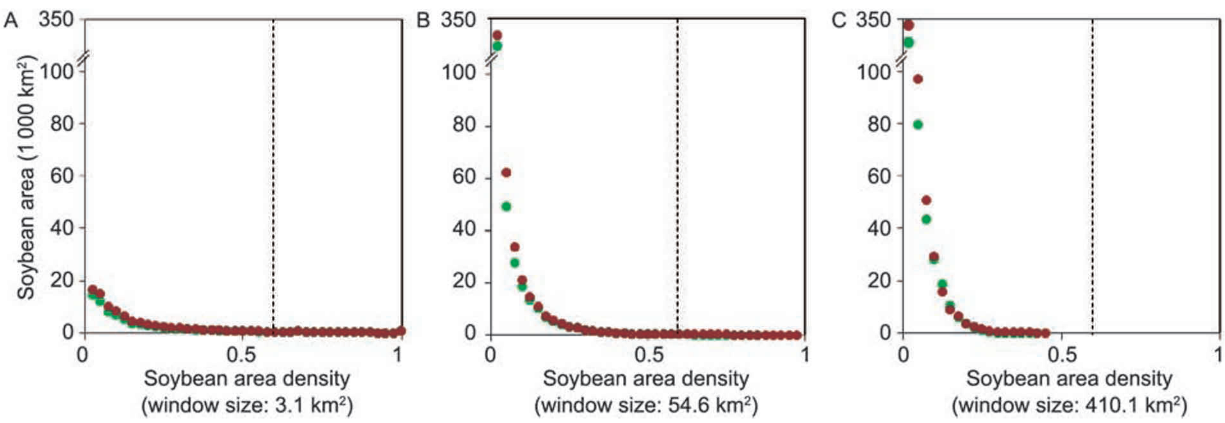

Fig. 6 Soybean area loss (red circles) and soybean rea gain (green circles) in relations to their soybean area density for selected widow sizes in MT.

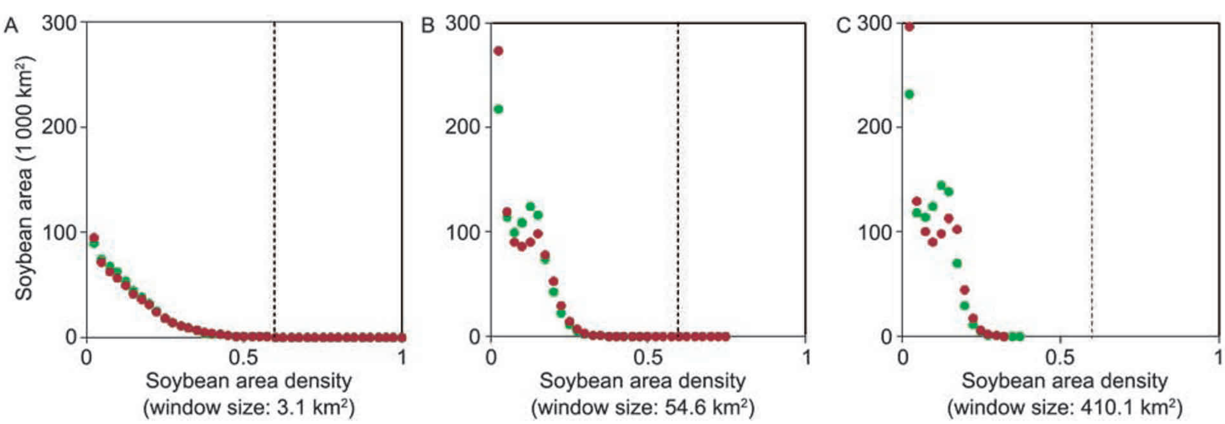

Fig. 7 Soybean area loss (red circles) and soybean rea gain (green circles) in relations to their soybean area density for selected widow sizes in WCB.

gain were distributed closely, which indicates its soybean lands were relatively stable, mainly due to the rotations with other crops like corn (Wright and Wimberly 2013; Lathuilliere *et al.* 2014). Export-oriented soybean expansion used to be widespread and had destroyed the Amazon rainforest at an unprecedented rate, in particular, the MT (Morton *et al*. 2006). Since the enforcement of the Soy Moratorium, the expansion trend has been effectively curbed (Gibbs *et al*. 2015). To meet the increasing soybean demand from the international trade, soybean cultivation has changed from area expansion to yield improvement (per-unit of land), i.e., agricultural intensification (Rudel *et al*. 2009), partially supporting the crop rotations explained here. Moreover, there were still some soybean expansions occurred outside the ecoregion in middle MT, which may demonstrate the increasing demands from international soybean trade and the effectiveness of conservation programs and governmental policies, like the Soy Moratorium. In WCB, soybean loss and soybean gain were also adjacent, partially due to the crop rotations. It was worth noting that we found the increase of intermediately dense soybean lands at the middle and large spatial scales in WCB. Because of planting flexibility, yield improvement (e.g., narrow-rowed seeding practices), and low production costs (Johnston 2014), soybeans are still a profitable crop and expanding in the United States. Nonetheless, corn is still the most-planted crop in the country, which could explain why the increasing soybean lands are intermediately dense. Also, average farmland size in the United States is about 5 km^2 (MacDonald *et al*. 2013), and thus the spatial scale 7×7 window (3.1 km^2) becomes too small to detect soybean land changes.

By studying spatial attributes, the identified hotspots of agricultural land-use changes provide important scientific information and policy implications for agronomic management and environmental conservation within and across trading countries. Locating hotspots of cropland gain and loss could inform whether they occurred in major crop production regions with high yield or they were spotted in agriculturally unfavored areas like those with bad soil fertility. For example, soybean lands experienced a substantial decline in China, but it is still the fourth largest soybean producer, and more importantly, it is the largest non-GM soybean producer (ASA 2015; Sun *et al*. 2015a). Increasing public concerns over the safety of GM crops has urged the Chinese government to preserve the production of domestic non-GM crops, such as soybeans (Wang 2010; Mao 2013). Thus, spatial analysis can provide critical information to the governments and related stakeholders and help them to target major soybean production regions with high yield (per unit of land) and thus increase production more efficiently. The identified hotspots of agricultural land changes also demonstrate the priority of environmental protection, i.e., the intersected areas between cropland change and ecoregions. Agriculture plays an important role in Brazilian economy, but the cropland expansion, such as soybeans, has also imposed considerable pressure on its environmental protection. Assisted by the spatial analysis, farmers, agronomic sectors and conservationist can work together to improve the food production while reduce negative environmental effects, such as relocating soybean expansion outside the ecoregions in middle MT identified here. Moreover, agricultural land-use changes are usually accompanied by agricultural pollution caused by the misuse/overuse of fertilizers and pesticides, and the pollution is widespread even for highly developed countries with advanced agricultural technology like the United States (Vitousek *et al*. 2009). Thus, our spatial analysis can help track agricultural pollutions. Alongside the management within trading countries, the results also inform policy makers among trading countries, helping strength international coordination. With the spatial information, China, in the north hemisphere, could better calculate soybean production and then assess the amount that needs to be imported. Then, Brazil, in the south hemisphere, can plan soybean cultivation accordingly. This enables Brazil to avoid deforestation caused by soybean over-expansion, and organize soybean production in a more environmental-friendly way.

Guided by the telecoupling framework, our analysis demonstrates the importance of spatial analysis, which enables effective management and coordination within and among multiple nations and thus better address international challenges. The telecoupling framework is a useful tool that helps people think more systematically and investigate human-nature interactions across multiple spatiotemporal scales, leading to important discoveries and practical applications. As a continuation of this telecoupling study and to promote a sustainable international trade, we will investigate the causes, agents, and flows among sending, receiving, and spillover systems of trading countries in the future, explore their socioeconomic and environmental effects, and transform the findings into policy and practice. The efforts will expand the understanding of complex issues in the international food trade, and therefore, offers constructive insights to better address global challenges.

5. Conclusion

Our results indicate that international food trade has caused different changes to the spatial patterns of soybean lands in telecoupled systems. Specifically, in receiving system Heilongjiang, soybean lands decrease in both west and east parts, while there are still some increase hotpots in west. In sending system MT, although the areas of soybean lands are relatively stable, they experience spatial relocation, i.e., newly expanded soybeans occur outside the ecologically vulnerable region. In spillover system WCB, soybean lands are stable spatially or even have some slight increase. In sum, we highlight the hotspots of soybean gain and soybean loss, and indicate these changes are spatially clustered, different across multi-spatial scales, and vary among the telecoupled countries.

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