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Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains

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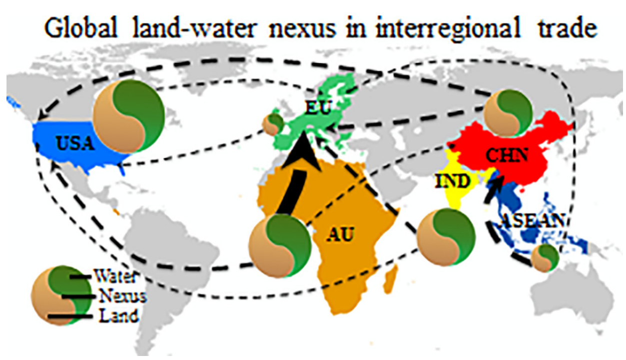
HIGHLIGHTS

- Agricultural land and freshwater use within global supply chains are tracked simultaneously.
- Land productivity and irrigation water requirements of 160 crops in different regions are investigated.
- Approximately one-third of land use and water withdrawal is attributed to interregional trade.
- Trade-off decisions should be made for both local agricultural production and global supply chain management.

GRAPHICAL ABSTRACT



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ABSTRACT

As agricultural land and freshwater inextricably interrelate and interact with each other, the conventional water and land policy in "silos" should give way to nexus thinking when formulating the land and water management strategies. This study constructs a systems multi-regional input-output (MRIO) model to expound global land-water nexus by simultaneously tracking agricultural land and freshwater use flows along the global supply chains. Furthermore, land productivity and irrigation water requirements of 160 crops in different regions are investigated to reflect the land-water linkage. Results show that developed economies (e.g., USA and Japan) and major large developing economies (e.g., mainland China and India) are the overriding drivers of agricultural land and freshwater use globally. In general, significant net transfers of these two resources are identified from resource-rich and less-developed economies to resource-poor and more-developed economies. For some crops, blue water productivity is inversely related to land productivity, indicating that irrigation water consumption is sometimes at odds with land use. The results could stimulus international cooperation for sustainable land and freshwater management targeting on original suppliers and final consumers along the global supply chains.

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Moreover, crop-specific land-water linkage could provide insights for trade-off decisions on minimizing the environmental impacts on local land and water resources.

1. Introduction

Agricultural land and water are the two most critical resources for life and food. Global per capita agricultural land is only about 0.7 hectares (ha), accounting for 37.9% of world's per capita land area (FAO, 2013). Meanwhile, per capital freshwater withdrawal amounts to 552.1 m^3/year, approximate to 70% of which is attributed to agricultural use (IDE-JETRO and WTO, 2011). Formidable population expansion (Godfray et al., 2010), rapid economic growth (Schneider et al., 2011), rising biofuel production (Gopalakrishnan et al., 2009) and more severe contamination (F-J Zhao et al., 2015) have together exerted great pressure on very limited land and freshwater resources. As land and freshwater resources scarcity escalates, the competition between agricultural, industrial and municipal demands will intensify (FAO, 2011). There are concerns that the increasing greenhouse gas emissions is likely to further exacerbate the pressure on land and freshwater resources, as the agricultural production and food supply is vulnerable to climate change (Piao et al., 2010; Schmidhuber and Tubiello, 2007). In the reality of geographical uneven distribution of these two natural resources, agricultural land and freshwater issues, such as transboundary water management (Voss et al., 2013) and land/water grabbing (Rulli et al., 2013), have been global hot spots in both academic and political circles. How to ensure the reliable availability of an acceptable quantity and quality of land and water resources has been a key issue for sustainable development.

There is growing recognition that globalization increases spatial separation of resource extraction, goods/services production and consumption with supply chains usually spanning multiple economies, leading to the shift of natural resources depletion and environmental degradation via international trade. For the global economic system, an empirically validated multi-regional input-output (MRIO) analysis, which is able to deal with the accumulation effect of environmental burden from upstream in global supply chains, has been widely used to capture the panorama of embodied resource/emission flows within intra-and international trade network. This has been well demonstrated for energy consumption (Chen and Wu, 2017; ZM Chen and Chen, 2011; Xia et al., 2017), greenhouse gas emissions (Davis et al., 2011; Peters et al., 2012), water use (Ewing et al., 2012; Feng et al., 2011; Hoekstra and Mekonnen, 2012; Lenzen et al., 2013), land use (Chen and Han, 2015; Weinzettel et al., 2013; Yu et al., 2013), material use (Bruckner et al., 2012; Wiedmann et al., 2015), biodiversity (Lenzen et al., 2012b), air pollutants such as $PM_{2.5}$ (Meng et al., 2016), atmospheric mercury (Chen et al., 2016; Li et al., 2017a; Liang et al., 2015), nitrogen pollution (Oita et al., 2016), sulfur dioxide, carbon monoxide and black carbon (Lin and Moubarak, 2014) and even socioeconomic impacts (Alsamawi et al., 2014; Simas et al., 2014). A consistent finding across these studies is that more developed economies usually import resource/emission-intensive goods/services at the cost of environmental burden transferring to less developed economies. Consequently, the conventional production-based accounting fails to capture the holistic picture of responsibility allocation and sustainability assessment (Chen et al., 2017a; Chen et al., 2017b; Chen et al., 2017c; Li et al., 2017b; Li et al., 2016), as both producer and consumer are regarded to bear a certain degree of responsibility of resources depletion and environmental degradation (Lenzen et al., 2007b). Therefore, in order to reasonably distribute resources as well as justly allocate responsibility, it is imperative to conduct a comprehensive embodiment analysis to track agricultural land and freshwater flows in global supply chains by applying MRIO approach.

Nowadays, as the engagement by land and water sectors becomes more proactive, the interconnectedness across land and water is increasing. As a result of the growing interdependence, management and governance of one resource will cause externality for the other one. For instance, the adoption of a specific land use change policy may have the potential to exert adverse effect on freshwater resources (Maes et al., 2009; Teixeira et al., 2014; Yira et al., 2016), indicating a strong nexus between agricultural land and freshwater. Meanwhile, international trade, especially food trade, could exert pressure on both land and water resources simultaneously (Antonelli et al., 2017; Rulli et al., 2013; Sandström et al., 2017). Therefore, conventional water and land policy in "silos" should give way to nexus thinking. The significance of nexus thinking among different resource elements has been addressed by many researchers (Al-Saidi and Elagib, 2017; Bazilian et al., 2011; Chen, 2016; Chen and Chen, 2016; Mo et al., 2014; Smidt et al., 2016; Valek et al., 2017; Wang and Chen, 2016; Yang and Chen, 2016). At present, many studies have also been carried out to evaluate different environmental elements simultaneously under a uniform ecological-economic system framework, enabling the tracking of environmental burden in the supply chains and a better assessment of the trade-offs among different environmental elements (Chen and Chen, 2011; Ewing et al., 2012; Galli et al., 2013; Shao et al., 2014; Steen-Olsen et al., 2012; Weinzettel et al., 2011). These studies lay the theoretical groundwork for assessing interrelation and interaction among different environmental elements using a consistent MRIO model. There have been many studies addressing global land and freshwater use embodied in international trade and final consumption separately (Chen and Chen, 2013; Lenzen et al., 2013; Weinzettel et al., 2013; Han et al., 2017), yet an assessment of combining agricultural land and freshwater use flows in the global supply chains has been lacking so far in the literature. It is vital to characterize simultaneously agricultural land and freshwater flows in global supply chains and reveal their interconnectedness.

Given the gap in current knowledge, this study constructs a systems MRIO model to simultaneously track embodied agricultural land and freshwater use flows along the global supply chains in 2012, from the source of land exploitation and water withdrawal by producers to the sink of final demand by consumers for 188 individual economies. Furthermore, land productivity (an indicator to measure how much crops is produced by per hectare arable land) and blue water consumption (an indicator to measure how much irrigation water consumed in a crop period to produce per kg crop) of 160 crops in different economies under different water stress levels are investigated to help make trade-offs decisions on local land and water resources. The results could 1) facilitate the understanding of responsibility allocation and stimulus international cooperation for sustainable land and freshwater management focusing on the two ends of the global supply chains; 2) show the interdependence of the two resources use flows within global supply chains, facilitating integrated management policies for sustainability and ensure the security of both resources via international trade; 3) provide insights for tradeoff decisions on minimizing the environmental impacts on local land and water and maintaining sustainable agricultural development from the perspective of nexus.

2. Methods and data

2.1. Systems MRIO model

For the embodiment analysis of resource use in the global economic system, a systems MRIO model integrating both direct resource use and monetary flows is constructed. A brief explanation about theoretical origin of systems MRIO model can be found in Supporting Information. As