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Water resources conservation and nitrogen pollution reduction under global food trade and agricultural intensification

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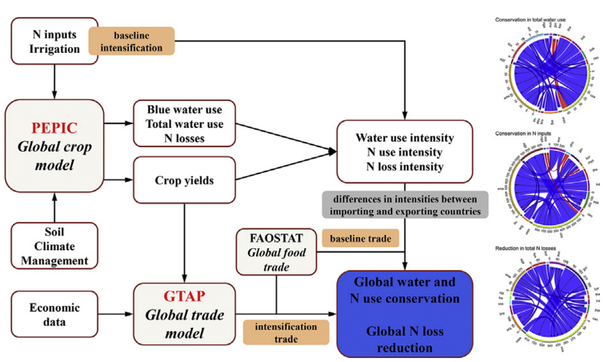
HIGHLIGHTS

- We investigate flows of water resources and nitrogen (N) pollution associated with international food trade.
- A grid-based crop model is combined with the Global Trade Analysis Project model for the investigation.
- Global trade of three major cereal crops conserves water and N uses and reduces N losses.
- Agriculture intensification increases crop yields but reduces food-trade related water and N savings and pollution reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

Global food trade entails virtual flows of agricultural resources and pollution across countries. Here we performed a global-scale assessment of impacts of international food trade on blue water use, total water use, and nitrogen (N) inputs and on N losses in maize, rice, and wheat production. We simulated baseline conditions for the year 2000 and explored the impacts of an agricultural intensification scenario, in which low-input countries increase N and irrigation inputs to a greater extent than high-input countries. We combined a crop model with the Global Trade Analysis Project model. Results show that food exports generally occurred from regions with lower water and N use intensities, defined here as water and N uses in relation to crop yields, to regions with higher resources use intensities. Globally, food trade thus conserved a large amount of water resources and N applications, and also substantially reduced N losses. The trade-related conservation in blue water use reached 85 $km^3\ y^{-1}$, accounting for more than half of total blue water use for producing the three crops. Food exported from the USA contributed the largest proportion of global water and N conservation as well as N loss reduction, but also led to substantial export-associated N losses in the country itself. Under the intensification scenario, the converging water and N use intensities across countries result in a more balanced world; crop trade will generally decrease, and global water resources conservation and N pollution reduction associated with the trade will reduce accordingly. The

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study provides useful information to understand the implications of agricultural intensification for international crop trade, crop water use and N pollution patterns in the world.

1. Introduction

Global food trade not only redistributes food supply between trading countries but also entails flows of imbedded water resources, resulting so called virtual water flows. Water resources are to a greater or lesser extent bound to the place where they occur, but the possibility to use them for producing export products makes them global (Hoekstra, 2017; Hoekstra and Hung, 2005). It has been estimated that around the year 2000 the volume of virtual water flowing throughout the world as a result of international food trade amounted to one-fifth of total water consumption for agricultural production (Hoekstra and Mekonnen, 2012). With the expansion of international trade, virtual water trade has been increasing during the past few decades (Antonelli et al., 2017; D'Odorico et al., 2014; Kastner et al., 2014). The influence of inter- or intra-national food trade on water resources utilization across trade partners has been intensively studied (Antonelli and Tamea, 2015; Ercin and Hoekstra, 2014; Feng et al., 2014; Porkka et al., 2017; Wang and Zimmerman, 2016; Zhang et al., 2012; Zhao et al., 2015; Zhuo et al., 2016).

In addition to water, other agricultural resources as well as environmental quality are influenced by international food trade. In particular, impacts on nutrients such as nitrogen (N) (Lassaletta et al., 2016; Liu et al., 2016a; Oita et al., 2016; Smil, 1999) and phosphorus (Lun et al., 2018; Nesme et al., 2016), land (Fader et al., 2011), water pollution (O'Bannon et al., 2014), deforestation (DeFries et al., 2010), and fine particulate matter ($PM_{2.5}$) (Zhang et al., 2017) have been studied. For instance, it was estimated that about a quarter of global N emissions were driven by demand for international trade in 2010 (Oita et al., 2016).

International food trade could serve to conserve global agricultural resources and alleviate environmental degradation if food were to be exported from regions with lower resources use and pollution intensities, where intensities are defined as the ratios of resources use and pollution emissions to crop yields, to regions with higher resources use and pollution intensities. Whereas the impacts of food trade on water conservation have been widely studied (Chapagain et al., 2006; Konar et al., 2016; Oki and Kanae, 2004; Yang et al., 2006), the effects of food trade on conserving other resources and reducing environmental pollution are still largely unclear (Dalin and Rodriguez-Iturbe, 2016). Furthermore, investigations of trade impacts on resources use and pollution have mainly been conducted by considering one metric at a time, e.g. either N (e.g. Oita et al., 2016) or water (e.g. Dalin et al., 2017). For some specific regions, a few studies have attempted to investigate such impacts through considering multiple aspects. For example, Martinez-Melendez and Bennett (2016) explored the impacts of food trade between the USA and Mexico on land, water, and N fertilizer use, as well as on nitrous oxide (N_2O) emissions, and concluded that the trade between the two countries reduced the environmental costs of agriculture. Zhao et al. (2016) included water, chemical oxygen demand (COD), and ammoniacal nitrogen (NH_3-N) to explore the burden shifting of water quantity and quality stress from Shanghai, the largest megacity in China, to its domestic trading partners. On a global scale, MacDonald et al. (2015) applied a multi-metric method to investigate the effects of global agricultural trade by considering economic, nutritional, and environmental dimensions of globalization and concluded that multi-metric research on global agricultural trade is important to interpret trade composition and structure. However, their study did not explicitly explore the extent to which agricultural trade can save resources and reduce environmental impacts. There is a lack of literature employing a multi-metric perspective on the beneficial gains of international food trade for resources and environment, not only regarding the past but also for a future of intensification in agriculture. Such an assessment is essential for improving our broader understanding of the impacts of trade on a global scale (MacDonald et al., 2012; Yang et al., 2013).

Here, for the first time, we performed a comprehensive global-scale investigation of trade effects for the three major crops—maize, rice, and wheat—on conserving water resources use and reducing N emissions to the environment, comparing the baseline situation around the year 2000 to a scenario of agricultural intensification. The three crops accounted for about 55% of global total virtual water flows of 38 different crops considered in Hoekstra and Hung (2005). A multi-metric perspective of global food trade effects was explored by taking blue water use (BWU), total water use (TWU) and N inputs (N_{in}), as well as N losses from agriculture to water (N_w) and the total environment (N_t) into consideration. BWU refers to the evapotranspiration (ET) derived from irrigation water applied to crop fields, also referred to as blue water consumption. TWU includes BWU and green water use. It refers to total ET, i.e. the sum of ET from irrigation water (blue water) and rainwater (green water). N emissions from crop production due to N fertilization were considered here mainly due to their significant impacts on human and ecosystems' health (Liu et al., 2017; Sutton et al., 2013; Zhu et al., 2005). Both water and N fertilizers are essential for crop growth and they affect agricultural performance in an interactive way (Mueller et al., 2012). Depletion of global water resources, especially blue water, and emissions of N from fertilization to environment have become critical concerns in many parts of the world (West et al., 2014). Therefore, investigation on the five important aspects relating to tradeoffs of crop production and environmental impacts in both exporting and importing countries can provide useful information to support the integrated management of water, food and environment.

In this study, a physical- and grid-based crop model Environmental Policy Integrated Climate (EPIC/PEPIC) was combined with the Global Trade Analysis Project (GTAP) to conduct the investigation. In addition to the baseline calculations, we also considered an agricultural intensification scenario, in which we assumed increases in N inputs and irrigated cultivation areas. The purpose of the scenario analysis was to illustrate possible impacts of agricultural intensification, which is advocated for achieving larger crop yields and production enhancement in low-input regions (Mueller et al., 2012), on global water resources conservation and environmental quality. The trends demonstrated in the intensification scenario reflect a general situation under any other agricultural intensification. The study provides useful information for understanding the complex implications of agricultural intensification for international crop trade, crop water use and N pollution patterns in the world.

2. Methodology and data description

In this study, we combined EPIC/PEPIC and GTAP to investigate water and N use conservation and N pollution reduction associated with global food trade under the baseline and intensification scenarios. Fig. 1 presents the schematic of the analytical framework used in this study, while our methodology is briefly summarized below with more details in following sub-sections.

We used the EPIC/PEPIC model (Liu et al., 2016b; Williams et al., 1984) to simulate agricultural BWU, TWU and N_{in}, as well as N_w and N_t. To investigate the impact of trade on these variables, we first