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Evaluating agricultural grey water footprint with modeled nitrogen emission data

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ABSTRACT

Food production is one of the major water pollution sources, due to the consistently intensive nutrient loss it generates. Grey water footprint (GWF) is commonly used as the indicator to assess environmental performance of human activities and water quality management. Current quantification of GWF mainly depends on existing parameters, sparse environmental census and monitoring, and hydrological models, which may lead to an inefficient evaluation of water pollution. Here, we apply a more applicable and flexible methodology based on modelled nitrogen emission inventories and water quality standards, to evaluate the GWF of food production with detailed food types and production process. We found that reactive nitrogen dominates the hydrological pollution in food production at the national level, and hence we quantified the emissions with details of processes, food types and Chinese regions. The GWF intensities (GWF of per kg food) of vegetable food products from this research were generally 3–70 times larger than those from key previous studies, while the animal food products showed even larger differences. However, our reasonable and comparable reactive nitrogen results bring additional confidence to the GWF results. As the quantification of reactive nitrogen emissions can easily fit into the targeted temporal and spatial range, the example introduced in this research can help to recognize the key food type and production process.

1. Introduction

Global water scarcity is caused by both actual shortages and progressive deterioration of water quality. Water pollution is also one of the most challenging environmental issues, in watersheds all over the world, and agriculture is a dominant contributor to water pollution, primarily because of fertilizer use and manure management (Liu and Yang, 2012; Mateo-Sagasta et al., 2017). About two-thirds of the major rivers in the world, especially in tropical and subtropical regions, are polluted at a level that exceeds their natural assimilation capacity (Liu et al., 2012). Increasing global population and changing dietary habits are creating even more challenges to water sustainability (Dalin et al., 2017). Food production uses multiple resources and causes environmental impacts such as water consumption, nutrient loss, and greenhouse gas (GHG) and chemical oxygen demand (COD) emissions. Chinese agricultural production has been steadily increasing in recent years, and is directly correlated with an increase in fertilizer use (NBSC, 2016). The concentrated pollutants emitted to water bodies require large volumes of water in order to be diluted sufficiently to meet the water quality standards of their regions. The amount of water used for this dilution is termed the grey water footprint (GWF) (Hoekstra and Mekonnen, 2012). GWF is the key indicator for water pollution assessment, and can facilitate the quantification of water pollution and hence the development of environmental policies and regulations. But the quantification of GWF still depends on existing parameters, sparse environmental census and monitoring, and hydrological models previously developed, which may have limited temporal and spatial ranges and may have been scaled from larger or smaller regional levels. In order for agricultural GWF to be accurate and useful, however, it should be quantified from the pollutants emitted to specific water bodies in a

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specific period of time. In this research, we aimed to provide a flexible and reproducible example of quantification and benchmarking with material flow analysis (MFA) of anthropogenic and natural nitrogen cycling, and thus contribute to more detailed and reliable information about the actual extent of water pollution.

Water footprint (WF) is an integrated indicator measuring total water consumption, including green water, blue water and grey water (Hoekstra and Mekonnen, 2012). These categories include water resources from rainfall, freshwater (both surface water and groundwater) withdrawal, and pollutant assimilation, and reflect the water requirements of various human activities. WF has been used as the metric in water management at the city level (Kang et al., 2017a), the watershed level (Zhuo et al., 2014), the national level (Liu and Yang, 2012; Pahlow et al., 2015) and the planetary level (Hoekstra and Mekonnen, 2012), and is also a factor in nexus issues (Vanham, 2016) and sustainable development goals (SDGs) (Biggs et al., 2015). The WF of food systems has been central to discussions on water scarcity, food security and environmental sustainability (Hoekstra, 2008; Kang et al., 2017b; Mekonnen and Hoekstra, 2012). However, many studies often neglect GWF in food systems, since GWF does not mean direct water resources consuming (Dalin et al., 2015; Eshel et al., 2014; Zhuo et al., 2014). Some studies have included GWF, but their quantification methods have been dependent on sparse environmental statistics (Cai et al., 2017), such as the Pollution Sources Census of China, which has only been surveyed for the years 2007 and 2017, or on existing coefficients with less regard for temporal or special variances (Gil et al., 2017; Li et al., 2017). Some accounting frameworks, such as the 'Water Footprint Network' (Hoekstra et al., 2011b), developed detailed standards and databases for the three types of water footprint, but these data are static and the factors reflect only the period 1995–2005. Another large-scale model, the Environmental Policy Integrated Climate Model (Liu et al., 2016a), specifies different water quality standards and various pollutants, but case studies show that only a few types of crops such as maize have been included (Liu et al., 2017).

Grey water footprint of agricultural production is usually quantified with nitrogen load to freshwater and local water quality standard (Hoekstra et al., 2009; Mekonnen and Hoekstra, 2015). We also select reactive nitrogen as the dominant indicator, after a comparison (see Methodology and Table 1) among the GWF calculated from several agricultural contaminants emitted to water bodies, including total nitrogen, ammonia nitrogen, phosphorus, and chemical oxygen demand (COD). Nitrogen emissions can be gained from material flow analysis (MFA) within a defined system boundary and localized activity data and parameters, which have been well-established anthropogenic nitrogen flow framework in previous studies(Cui et al., 2013; Gao et al., 2018; Gu et al., 2015). We argue that GWF assessment should consider the spatial and temporal variances of pollutants, and specify various food types, to address the changes in food production technology that are being promoted and widely adopted in China. An effective quantification of the GWF indicator can facilitate further analyses such as virtual water trade, the effect of dietary changes, nexus study, life-cycle analysis (LCA), and policy design. But most previous methodologies on grey WF accounting have been either relatively limited in detail or too time-consuming or labor-intensive, for several reasons. First, methodologies that rely on existing factors or statistics can hardly capture the up-to-date and changing status of water pollution evaluation. Updating the model would consume scarce research resources, and it would still not be possible to keep up with the newest trends in the field. Second, no static model can accurately reflect the contaminant removal efforts made by farmers, or the effects of new regulations from local governments. Third, most of the researches do not dive into the details of emission sources for each food type, and thus fail to reflect production technology and patterns such as fertilizer use intensity, straw and manure recycling, or yield improvements.

Table 1
Grey water footprints calculated from the Pollution Sources Census of China (year 2007).

	COD	Total N	Total P	Ammonia N
Emissions, kt	13240.5	1633.5	236.2	238.6
Standards, mg/L	20.0	1.0	0.2	1.0
Grey WF, Gt	662.0	1633.5	1180.9	238.6

The contribution of this research is, therefore, to provide details of processes (emission sources) of the GWF for each food type derived from cropland, livestock, and aquaculture systems by applying nitrogen modelling and making the evaluation more simplified, flexible and reproducible. With the nitrogen flow modelling of agricultural production, as shown in this research, researchers and other stakeholders can quantify the water pollution level within the targeted administrative boundary and time period (not just a few certain years with environmental emission statistics) with detailed food type and production process, and proceed to further evaluations. Our detailed results for the GWFs of these processes and food types will contribute to the analysis of sustainable agriculture, technological improvements, fertilizer optimization, and normalized GWF for specific food types, which can provide beneficial information to the debate on dietary shifts, human health, and the interregional benchmarking of technology and environmental performance.

2. Methodology

2.1. Selecting an indicator

Grey water footprint (GWF) is an indicator of freshwater pollution, defined as the volume of water needed to dilute the pollutant load, based on the official water quality standards. The grey WF is calculated by dividing the modeled or observed pollutant load by the concentration gap between the ambient water quality standard for that pollutant and the receiving water body (Hoekstra et al., 2011a), as shown below:

$$\mathrm{GWF} = \max_{p}\left(\frac{L_p}{C_p - C_n}\right) \tag{1}$$

where L_p is the volume of pollutant p; C_p is the largest acceptable concentration of pollutant p according to the local water quality standard; and C_n is the natural concentration of pollutant p in the receiving water body with no disturbance in the catchment by humans; this is usually assumed to be zero (Franke et al., 2013). Wastewater discharges carry many materials, but the amount of freshwater needed for dilution is determined by the key pollutant, and thus we took the largest results calculated from function (1) for various pollutants.

The main pollutant sources in food production include chemical oxygen demand (COD), biochemical oxygen demand (BOD), reactive nitrogen (Nr), and phosphorus (P) loss to surface and groundwater, mainly due to the application of various fertilizers and to manure management, from cropland, animal husbandry, or aquaculture systems. The First Pollution Sources Census of China, published in 2010, considered the emissions of Chemical Oxygen Demand, total Nitrogen, total Phosphorus, and Ammonia Nitrogen, which affected water quality in the year 2007 (Table 1). The acceptable concentration of pollutant C_p in this study was taken as the value in Grade III according to the Environmental Quality Standards for Surface Water in China (MEP, 2002). This standard is for surface water, but other countries like the U.S. set standards for drinking water which have a higher value (Liu et al., 2017). With a preliminary calculation of GWF from all the major agricultural pollutants, the GWF from total nitrogen discharge was found to be the largest. Thus we can conclude that nitrogen emissions dominate the GWF of food production, and this conclusion is in accordance with the approaches of previous studies (Cai et al., 2017; Li et al., 2017; Mekonnen and Hoekstra, 2015).