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A hybrid method for quantifying China's nitrogen footprint during urbanisation from 1990 to 2009

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ABSTRACT

In this study, we devise a national nitrogen footprint method to evaluate the life cycle nitrogen flows through the national economy of China from 1990 to 2009. To this end, we build a hybrid method based on two well-established techniques, namely material flow analysis (MFA) and input-output analysis (IOA). This integration allows for the evaluation of the effects of international trade and interdependencies among economic sectors. Our results suggest that China's nitrogen footprint (NF) has increased from 30.3 Teragrams (Tg) in 1990 to 54.0 Tg in 2009, whereas the NF per capita has increased from 25.9 to 39.5 kg N/yr. Relationship between the world NF per capita and human development index (HDI) appears to show an inverted U curve, whilst China shows an increase both in NF per capita and HDI. We find that an increase in China's NF is largely associated with high levels of urbanisation. Although the energy NF (E_NF) has increased more drastically than the food NF (F_NF), the latter still dominates China's total NNF, with proportions of 91% in 1990 and 82% in 2009. Taking international trade into account, our results demonstrate that China was a net exporter of F_NF, whilst a net importer of E_NF over this time period. There are many measures considered to reduce China's nitrogen footprint, including improvements in N use efficiency of food systems, transformation of meat-based diets and optimisation of China's economic structure.

1. Introduction

Nitrogen (N) pollution causes severe damage to the environment at local, regional, and global scales. This pollution is primarily caused by human activities associated with the demand for food and agricultural products, thus resulting in significant quantities of reactive N (referred hereon as Nr - i.e., any form of the element N other than the non-reactive atmospheric gas N_2) into the environment (Vitousek et al., 1997; Gruber and Galloway, 2008). In addition to the creation of Nr for feeding and supplying goods to the local population, an increase in the global trade of Nr-embodied commodities has further exacerbated the environmental damages caused by the release of excess Nr (Galloway et al., 2008), thereby further raising the socioeconomic costs of environmental damages (Naylor et al., 2005). This is particular true for China, which is the top exporter of Nr-embodied commodities to developed nations such as the USA and Japan (Oita et al., 2016). Whilst it has been established that Nr creation continues to increase every year (Galloway et al., 2008; Cui et al., 2013); its disproportional distribution results in N surpluses in some regions and N scarcities in others (Liu et al., 2010). One factor driving these extremes is urbanisation, which results in large concentrations of Nr, a situation made worse in areas with high people density (Wickham et al., 2002). It is of utmost importance to quantitatively evaluate the human-induced Nr emissions, such that effective strategies and policies could be devised for mitigating the harmful effects of excess Nr. The concept of a "footprint" has become a well-established method for describing how human activities impose various types of burdens and impacts on Earth's life support systems (UNEP/SETAC, 2009). The main types of environmental footprints calculated so far include carbon, water and ecological footprints, forming the so called "footprint family" (Galli et al., 2012). Their underlying calculation methods and corresponding online calculators have gained increasing public attention and have been applied at several scales. Whilst the N footprint (NF) has emerged more recently and is less known, it is commonly considered as an ecological indicator of the amount of Nr released into the environment from human activities (Cucek et al., 2012; Leach et al., 2012). It is also an index of the extent of disruption of the regional or global N cycle, and of the environmental consequences of anthropogenic perturbation (Bakshi and Singh, 2011). Thus far research has primarily been directed towards calculating the NF of a product (e.g.

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food or energy generation) (Bakshi and Singh, 2011; Xue and Landis, 2010; Cucek et al., 2011), however considerably less emphasis has been placed on quantifying the NF of an entire national or regional economy. Leach et al. (2012) first coined and developed a NF model and an online N-Calculator that can estimate how much Nr a country, institution or individual releases to the environment. The study of Gu et al. (2013a) attempted to assess the national NF (NNF) of China based on an N-mass balance approach, however, they only considered the production perspective and not the emissions resulting from the consumption of goods and services (consumption perspective). The most comprehensive NF to date was undertaken by Oita et al. (2016), who calculated both the production and consumption-based NF of 186 world nations. For conducting the footprint assessments, they used the famous input-output equations, based on the well-documented input-output theory formulated by the Nobel Prize Laureate Wassily Leontief (Leontief, 1936, 1953, 1970; Leontief and Strout, 1963; Leontief and Ford, 1972).

It has been established that, globally, Nr transfer through trade is larger than the rate of Nr creation (Galloway et al., 2008). Urbanisation also calls for an increase in internal or external demands for supporting humans. Imports and exports therefore cannot be neglected for an increasing open economy (Machado et al., 2001). China plays an important role in the international trade of Nr-embodied commodities (Oita et al., 2016). It is therefore crucial to quantify the combined effect of urbanisation and international trade on China's emissions over the past decades, a time period characterized by rapid urbanisation and economic growth (Cui et al., 2013; Fischer et al., 2010; X.J. Liu et al., 2013). Here we construct a national NF (NNF) model to measure the total volume of Nr emissions for China from 1990 to 2009, that are directly or indirectly caused by nationwide food and energy production, consumption and trade.

Our model integrates the dimension of urbanisation and contribution of international trade into one framework, for determining and quantifying the sources and dynamics of China's NNF from 1990 to 2009. This NNF model takes into account all "life cycle" Nr released to the environment by demand for food and energy. The advantage of our demand-oriented approach is that it offers a consistent methodology for facilitating nationwide comparisons, better estimates of the indirect NF embodied in national demand (including domestic production, consumption, trade of food and energy), and discovery of possibilities for mitigating or preventing Nr pollution. Key challenges to modeling China's NNF arise from the need to account for the internal and external effects of international trade, as well as for interdependencies among economic sectors, in order to express and quantify the virtual and embodied Nr fluxes through the national economy.

2. Methods

2.1. National nitrogen footprint (NNF) model

Our NNF concept is closely linked to the idea of virtual N at product level, analogous to the idea of virtual water (as opposed to real water) (Allan, 1994) and encompasses the total amount of Nr released to the environment during the production, use and disposal of the product or service. Our NNF model builds on and extends existing models by Leach et al. (2012) and Gu et al. (2013a) in many ways; details are given in Appendix A. The general segregation of NNF into food and energy sectors is included in the methodology developed by Leach et al. (2012) and is represented as: food NF (F_NF) and energy NF (E_NF). Both can be expressed in total units of Nr and evaluated from environmental and economic flow perspectives, respectively:

$$NNF = F\_NF + E\_NF \quad (1)$$

In particular, we segregate the NNF into respective domestic, import and export components; the later ones is not included in the Leach et al. (2012), which represents Nr created by international trade, i.e. the imported and exported NF (NF_{in} and NF_{ex}). NF_{in} is considered as emissions embodied in the imported goods and services, and represents Nr emissions in the source regions of the imports. In contrast, NF_{ex} is considered as emissions embodied in the exported goods and services, and represents Nr produced in the study region. Drawing on the calculations of national water footprint by Hoekstra and Chapagain (2007) and those of NF by Leach et al. (2012), the NNF model can be further refined as Fig. 1), and the components can be delineated in Table A1. More specifically, our analysis is based on nationwide agricultural and energy activity statistical data and allows for formulation and calculation of Nr inputs into and flows between different stages, sectors and regions. This is especially important since we are able to analyse responsibility transfers and trade-offs among different stages, sectors and regions for Nr environmental loads by application of a method combining the well-established physical (material flow analysis MFA) and an economic (input-output analysis IOA) model.

2.2. NNF due to food consumption

The domestic F_NF (F_NF_{dom}) represents the total Nr losses associated with Nr applied to the internal food production system, and consists of two essential parts: food production NF ($F\_NF^{p}_{dom}$) and food consumption NF ($F\_NF^{c}_{dom}$). We consider 14 major food types here: cereals, starchy roots, sugarcrops, pulses, oilcrops, vegetables, fruits, beef,

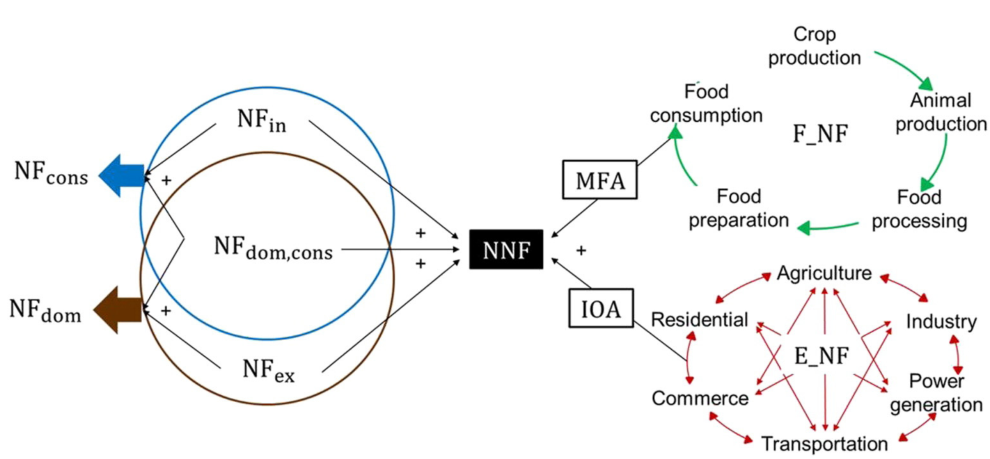

Fig. 1. Calculation framework of NNF based on a hybrid method. $NF_{dom, cons}$ is the domestic consumption NF, meaning the Nr emission resulting from internal production used for internal consumption. NF_{dom} is the domestic NF, meaning the Nr emissions resulting from both production and consumption within the internal region. NF_{cons} is the consumption NF, meaning the Nr emissions resulting from both internal and external production used for internal consumption.