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Top-down approach to estimating the nitrogen footprint of food in Japan

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ABSTRACT

In this paper, we propose a new methodology for estimating the nitrogen footprint of food, which has recently been identified as an indicator of human interference in the environment, specifically due to our global production and consumption of food. N-calculator is the common method of nitrogen footprint estimation, which evaluates nitrogen outputs into the environment at each step from crop production to food consumption based on Virtual Nitrogen Factor (VNF). For heavy food importers like Japan, however, it is difficult to get suitable VNFs of exporting countries. Our method is a top-down approach for estimating new external nitrogen inputs from chemical fertilizers and biological nitrogen fixation (BNF) used within the country (i.e., direct inputs), as well as in food-exporting countries (i.e., indirect inputs) that export to Japan; our approach is based primarily on open access statistical data, not on VNFs. In this present study, we measured nitrogen inputs for 110 combinations of food items and exporting countries; from our evaluations, the estimated nitrogen footprint of Japan was 16.5–18.1 kg N capita^{-1}, of which direct inputs constituted approximately 5.5 kg N, leaving more than two-thirds as indirect inputs from food imports. The nitrogen footprint of Japan was smaller than those of the USA and some European countries, but we calculated the nitrogen footprint to be 27.8 kg N capita^{-1}, i.e., larger than all other countries, when all consumed food was assumed to be produced in Japan, and the significant increase in nitrogen input was caused primarily by less efficient crop production in Japan than by exporting countries. Overall, our results were much smaller than previous estimations of footprint of Japan based on the common method in which all imported food is assumed to come from the USA because of the difficulty in using VNFs for many exporting countries. Although our results have uncertainties, based on our results, we consider our method to be suitable for estimating the nitrogen footprint of countries that significantly rely on imported food, much like Japan.

1. Introduction

The nitrogen footprint is a recently established per capita indicator for estimating nitrogen outflows into the environment caused by human activities for particular countries. It aims to be a member of the “Footprint Family” proposed by Galli et al. (2012) that includes the ecological, carbon, and water footprint (Leach et al., 2012). Due to a variety of human activities, including agriculture, transportation, industry, and so on, the earth has been enriched with nitrogen, and as a result, the environment (i.e., atmosphere, water, soil, etc.) has been severely damaged in wider areas (Erisman et al., 2008; Galloway et al., 2003, 2004, 2008; Sutton et al., 2011). Recognizing such damage and potential for more, various approaches have been proposed and implemented to estimate nitrogen flow and environmental impacts (Galloway et al., 2004; Gu et al., 2013a; He et al., 2011; Lin et al., 2001; OECD, 2001; Ma et al., 2012; Seitzinger and Kroeze, 1998; Shindo et al., 2009). In these previous estimates, the key objective was to evaluate the abundance and flow of nitrogen exported into the environment on various geographical scales ranging from global to individual countries to small catchments. Further, proposed countermeasures to prevent continued environmental deterioration primarily consisted of production efficiency, i.e., wise uses of nitrogen, efficient energy use, recycling of livestock manure, and so on.

As a new approach, the nitrogen footprint is defined as an estimate of nitrogen released into the environment as a result of

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consumption patterns of food, energy, and so on by consumers (Leach et al., 2012) and N-calculator model and N-Institution model were developed for calculation of nitrogen footprint for individuals and institutions (Leach et al., 2012, 2013; http://www.N-Print.org) in which people's way of life such as dietary customs the reliance on fossil fuels are the major concern. These models take a bottom-up approach in which nitrogen released into the environment is estimated as per unit consumed nitrogen (Leach et al., 2012). In case of nitrogen footprint of food, the amount of nitrogen released at each step is evaluated from food production to consumption; more specifically, this includes nitrogen not used by crops, crop processing waste, food processing waste, food waste, human waste (i.e., consumed nitrogen as food) for vegetal food, and additionally manure loss, slaughter waste, and meat processing waste for animal food (Leach et al., 2012). Based on these nitrogen release data, a virtual nitrogen factor (VNF), i.e., the ratio of total nitrogen released before consumption to nitrogen in human waste is evaluated for each major food item, then the total released nitrogen is estimated from these VNFs and the consumption rates of various types of food. Using this bottom-up method, the nitrogen footprint of food has recently been estimated for several countries, including Japan (Galloway et al., 2014; Leach et al., 2012; Pierer et al., 2014; Shibata et al., 2014; Stevens et al., 2014).

Further, different approach, so called top-down approach has also been proposed for the nitrogen footprint estimation, which employs nitrogen flow models (Bleeker et al., 2012; Gu et al., 2013b; Leip et al., 2014; Oita et al., 2016a). Leip et al. (2014) evaluated the nitrogen release to the environment per unit amount of production of various kind of food items, not per capita estimate. Oita et al. (2016a) specifically focus on nitrogen pollution embedded in international trade for 188 countries and showed Japan had the maximum nitrogen release due to net import.

Japan imports large amounts of food of various kinds from many countries. Based on food balance sheet data of FAOSTAT (FAO, 2015), nitrogen in food produced in Japan was 460 Gg N in 2011, whereas nitrogen in net imported food and feed was 966 Gg N, more than 2 times that of production. To estimate an N footprint that accurately reflects the reality of food supplies, it is necessary to consider international trade. Shibata et al. (2014) estimated the nitrogen footprint of food for Japan both with and without food trade data using the N-calculator model, showing that food trade had a significant effect in reducing the nitrogen footprint form 34.5 kg N capita^{-1} year^{-1} to 25.6 kg N capita^{-1} year^{-1}. In their estimation, VNF values for the USA were used to estimate the virtual nitrogen of all imported foods, because VNFs for most of the exporting countries were not available.

In this paper, we propose a different method, i.e., a top-down approach, for nitrogen footprint estimation that considers food imports from major exporting countries; our approach is also applicable to the without-trade cases, assuming all foods are produced in Japan. Our method primarily focuses on new nitrogen inputs used for food production in an objective country and also in food exporting countries and can estimate the footprint based on open access data without using any nitrogen flow models and VNF estimates, aiming at the application for countries where food is heavily imported and also appropriate VNFs are not available.

2. Materials and methods

2.1. Estimation method of nitrogen footprint with food trade

The origin of nitrogen released into the environment including human waste and retained in agricultural soil due to food production and consumption eventually consists of external new inputs of nitrogen from applications of chemical fertilizers and cultivation-induced biological nitrogen fixation (BNF). In bottom-up approach, nitrogen release to the environment is evaluated, while we estimated these inputs in Japan and exporting countries based on the framework of nitrogen flow shown in Fig. 1 in our top-down approach. We considered nitrogen inputs from fertilizer applications and BNF for (1) imported crops, (2) crops used for the production of imported vegetable oils, sugar, and alcohol, excluding non-food use, (3) crops used for production of imported livestock products and imported fed aquaculture seafood and (4) crops produced in Japan. We also considered non-fed aquaculture and captured seafood as external nitrogen input. Note that in the figure, these are indicated with bold arrows as external inputs. Conversely, nitrogen released into the environment via each nitrogen flow process is estimated using the common bottom-up method.

Although livestock manure and protein meal, such as oilcakes and brans, are important inputs for crop and livestock production, respectively, these were not included as inputs, because these are not new inputs, but rather are recycled nitrogen. In summary, we identify nitrogen inputs within Japan due to (4) and non-fed aquaculture and captured seafood above as direct inputs and other the inputs (1), (2), and (3) as indirect inputs.

Based on open access data obtained primarily from international organizations, we estimated each nitrogen input via methods described below. Overall, the Japanese data derived from our data sources were replaced with corresponding domestic data when these two datasets differed from one another to some extent. Food items and their corresponding classifications were primarily based on the Food Balance Sheet (FBS) of FAOSTAT (FAO, 2015) and food weight was converted to nitrogen based on protein content provided by FAO (FAO, 2001) and protein to nitrogen conversion rate proposed by Mariotti et al. (2008) for each food item. All values indicating amount, such as amount of food, nitrogen in it, fertilizer, BNF and resulted nitrogen footprint were expressed as values per year.

2.1.1. Nitrogen fertilizer and BNF for crop production in exporting countries

Based on "Detailed trade matrix" data of FAOSTAT (FAO, 2016a), major countries from which Japan imports were identified for each food item. Milk was imported as a processed good and, because it was difficult to identify the corresponding major export countries from FAOSTAT, we instead used information from the Ministry of Agriculture, Forestry and Fishery in Japan (Ministry of Agriculture, Forestry and Fisheries of Japan, 2004). Then the amount of nitrogen fertilizer used for the production of imported food $N_{F,IM}$ (Mg N) was estimated for each combination of country and food item via the Eq. (1):

$$N_{F,IM} = A_{IM} f_F \qquad f_F = N_{F,P}/A_P \tag{1}$$

Here, A_{IM} indicates the imported amount (Mg) of a particular food item from a particular country, $N_{F,P}$ represents the total amount of nitrogen fertilizer (Mg N) used for this food item production derived from the report by the International Fertilizer Industry Association (IFA) (Heffer, 2013), and A_P represents the total amount of production (Mg) of this food derived from FAOSTAT (FAO, 2016b). We call f_F (Mg N Mg^{-1}) the fertilizer rate. For exporting countries and food items not available in the IFA report, we used world average f_F of the food and average f_F of all foods of the country, respectively.

Regarding leguminous crop production, BNF due to the production of imported crops (i.e., $N_{BNF,IM}$) was calculated using the