博士論文

Improvement of Nitrogen Footprint Models: Analysis for Seafood and International Trade

窒素フットプリントモデルの改良
－水産物および国際貿易に着目して

国立大学法人 横浜国立大学大学院
環境情報学府

種田　あずさ

Oita Azusa

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Oita Azusa

Graduate School of Environment and Information Science

Yokohama National University

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Abstract

Humans are transforming the global nitrogen cycle by creating more reactive nitrogen (Nr; all species except N_2) than is created through natural processes every year. The excess Nr is created mainly by fertilizer use and fuel combustion. Since nitrogen is essential to grow crops, fertilizer use has been on a drastic increase to feed an ever-growing world population exhibiting increasing preference for animal products. However, the excess Nr in the environment has various negative effects, including eutrophication, climate change, acidification, and human health problems. The level of current human effects upon the cycle is roughly three times beyond the plant's safe operating space. Given the excess nitrogen contributing to the severe degradation of the marine ecosystem, urgent action is committed at the Rio+20 summit and included in Sustainable Development Goals.

The concept of footprint has been developed to analyse the resource requirements throughout the whole life cycle, initially as ecological footprint, followed by carbon footprint, water footprint etc. Two types of approaches have been applied to calculate environmental footprints in the literature: bottom-up and top-down approaches. Bottom-up approach refers to both a process-based life cycle analysis using detailed descriptions of individual production processes and a coefficient analysis based on analyses of individual production processes. The advantages of the approach are simplicity for understanding and sensitivity for accessing difference in product level. It is widely used in practical business. However, this approach does not trace the entire industrial supply chain, leading to inter-sectoral cut-off and inter-regional cut-off. Top-down approach refers to both a mass balance analysis based on national statistics and an economic input–output (IO) analysis using hierarchical models with total factor multipliers based on national economies to determine embodied effects per unit of production. The advantages of the approach are comprehensiveness for its coverage and, for IO analysis, capability for tracing the entire supply chains. Single-region IO (SRIO) analysis can capture inter-sectoral cut-off, and multi-region IO (MRIO) analysis can capture both inter-sectoral and inter-regional cut-offs. However, these methods are limited by the numbers of sectors in the IO database used, in analysing detailed consumption. It is commonly used in analyses on the national and supra-national level.

The nitrogen footprint (NF) concept has been introduced to show consumers' contributions to nitrogen pollution. NF measures the total amount of Nr emitted as a result of resource consumption. The previous NF model for individuals (the N-calculator method) consists of food NF and energy NF. Food NF was calculated by a flow-based model (bottom-up approach) with coefficients for efficiency, recycling, etc. Energy NF was calculated by a combination of bottom-up approach using activity data and emission

factors and a national level SRIO analysis. It has been applied to inhabitants, nations, institutions and specific food products, and extended to nitrogen emissions neutrality. Per-capita NFs have been calculated for the USA, the Netherlands, Germany, the UK, Japan, Austria, Portugal and Tanzania, but no studies revealed the global situation and the places affected by the NFs. Food was found to be the most dominant component and per-capita NFs for countries vary because of their diets. However, fish and seafood is calculated in a simple way similar to livestock, despite the share in the total protein intake (6.4%) similar to that of poultry meat.

In order to achieve significant reduction in Nr emissions by global integrated nitrogen management, this study focuses on the global analysis of NF (Chapter 2) and NF of seafood (including finfishes, crustaceans and mollusks, both inland and marine; Chapter 3), providing more detailed information for policy makers and consumers on their food choices to reduce their NFs.

In Chapter 2, the NFs for 188 countries are calculated as the sum of direct and indirect emissions they induce through their consumption, to air (ammonia NH_3, nitrogen oxides NO_x, consisting of NO and NO_2, and nitrous oxide N_2O; from all industries), and to water (nitrogen potentially exportable to water bodies Nwp, mainly potentially discharged nitrate NO_3^- from agriculture and sewage). Emissions data estimated from international fertilizer association data and FAOSTAT production and emissions data with coefficients from IPCC are linked to a global MRIO database of domestic and international trade for 15,000 sectors to calculate the NFs for nations. Per-capita footprints range from under 7 kg N yr^{-1} in some developing countries to over 100 kg N yr^{-1} in some wealthy nations. Four populous nations bear 49% of the global Nr emissions in their territories (China 20%, India 11%, USA 10%, and Brazil 6.1%), followed by another six nations (Russia, Pakistan, Indonesia, Australia, Mexico, and Argentina) bearing additional 12%. On the other hand, 46% of global emissions are induced by China (19%), India (11%), the USA (10%) and Brazil (6%), and additional 13% by another six nations (Japan, Russia, Indonesia, Germany, Mexico, and the UK). Roughly a quarter of the global NF comes from commodities that were traded across country borders. The main net exporters have significant agricultural, food and textile exports, and are often developing countries, whereas important net importers are almost exclusively developed economies. The results show that substantial local nitrogen pollution is driven by demand from consumers in other countries.

In Chapter 3, a new NF model is proposed to evaluate the impact of seafood in detail. The new model is applied to Japan as a case study, and the important parameters are explored for more accurate evaluation of NF of seafood. The new model tracks the feeding steps in detail, considering differences among fed aquacultured seafood, non-fed aquacultured seafood (mainly bivalves and filter-feeding carp), and captured seafood. The new model evaluates the Japanese food NF of fed aquacultured seafood as 0.7 kg N cap^{-1} yr^{-1}, ca. 45% of that of all seafood, whereas the previous model evaluates it as 3.36 kg N cap^{-1} yr^{-1}, ca. 90%. The key factors for assessing the NF of seafood are found to be the proportions of fed aquaculture and of plant protein in feed. In order to enable food choices that will effectively reduce nitrogen release, the virtual N factors (per intake reactive nitrogen release during production) for different seafood are provided as 0.2 (non-fed aquacultured and captured), 4.8 (freshwater and diadromous fish), 3.9 (demersal fish), 3.4 (pelagic fish and other marine fish), and 8.2 (crustaceans). The results show that eating more non-fed aquacultured and captured seafood and less fed-aquacultured shrimps and prawns could reduce our nitrogen load from food consumption as effectively as choosing poultry (virtual N factor of 3.4) instead of beef (8.5).

In Chapter 4, further discussion is conducted on the main findings and the methodology of each chapter, and scenario analysis on different diets is performed to explore the options for more sustainable diets. The results in Chapter 2 and FAOSTAT food balance data indicate that Asian countries including Japan and South Korea have relatively low per-capita NFs for NH_3 and Nwp, because of their diets with less meat. Using the new model developed in Chapter 3, four different diet scenarios are tested: (1) "Recommended level protein", cutting protein consumption down to the level recommended by Ministry of health, Labour and Welfare of Japan; (2) "Pescetarian", consuming more fish and seafood to replace the current protein consumption from meat; (3) "Low NF food", consuming more legumes and fish and seafood that is non-fed aquacultured or captured, to replace the current protein consumption of meat, dairy, egg, and fed aquacultured, fish and seafood; (4) "Balanced Japanese diet", consuming food as did in 1975, which is said to be good balanced in nutritional studies. All scenarios reduce the current food NF by more than 15%, and "Low NF food" scenario is the most effective choice among the all, dropping by 45%. These results show that not only by reducing the amount of protein we take, but also by choosing low NF food, we can reduce our food NFs. The above findings contribute to an integrated risk management to deal with trade-offs, including nitrogen pollution, stock depletion, human health, carbon emissions, etc.

NF can measure the environmental load of Nr for an individual level to the global level. It helps policy makers and consumers to understand that, through our choices on food and other commodities, we can achieve reduction targets of the human-induced Nr and to mitigate nitrogen pollution both in our local areas and in the areas where our food and other commodities come from.

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Statement on Publication and Joint Contribution

This dissertation is mainly comprised of two research papers, presented as Chapters two and three. Note that they are not presented in the order in which they were published.

Chapter 2: Substantial nitrogen pollution embedded in international trade

This chapter contains the following published paper with the exception of differences in formatting and small modifications to remove typographical errors and to improve clarity within the thesis:

> **Oita, A.**, Malik, A., Kanemoto, K., Geschke, A., Nishijima, S., & Lenzen, M. (2016). Substantial nitrogen pollution embedded in international trade. *Nature Geoscience*, 9(2), 111–115, doi:10.1038/ngeo2635.

I was the primary author, conducted the background research and wrote content for the paper (detailed in Figure 0.1). Arunima Malik conducted the environmentally extended input–output analysis (EEIOA), prepared the main figures, and contributed to the text, data interpretation and manuscript editing. Keiichiro Kanemoto assisted in the data preparation and contributed to data interpretation and review comments. Arne Geschke conducted the uncertainty analysis. Shota Nishijima assisted in the data preparation. Manfred Lenzen assisted with the design of the research, wrote content for the paper, and contributed to data interpretation and manuscript editing.

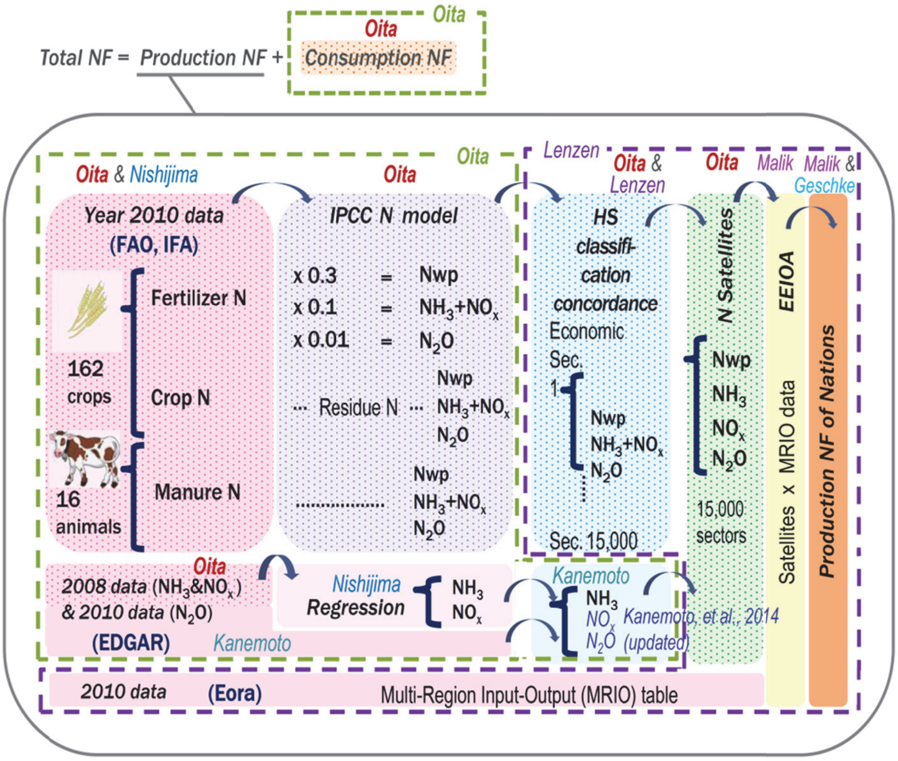

Figure 0.1 Authors' contribution to the paper included in Chapter 2. The names with the frames show contribution on design of the process and the names with the processes show contribution on data preparation and analysis.

Chapter 3: An improved methodology for calculating the nitrogen footprint of seafood

This chapter contains the following published paper as sections of abstract, introduction, materials and methods, results (except two of the figures), discussion (two of the three subsections), and conclusions with some small modifications to remove typographical errors and improve clarity:

Oita, A., Nagano, I. & Matsuda, H. (2016). An improved methodology for calculating the nitrogen footprint of seafood. *Ecological Indicators*, 60, 1091–1103, doi:10.1016/j.ecolind.2015.08.039

Figures 3.3 and 3.5 have been revised and the third paragraph of the subsection 3.5.2 "Nitrogen footprint for sustainable food choices in seafood-eating countries" in the discussion has been added in order to incorporate a comparison with Shibata *et al*. (2014). I was the primary author, conducted the background research, and wrote the paper. Ichiro Nagano assisted in the preparation and interpretation of the data, and provided review comments. Hiroyuki Matsuda supervised the research and contributed to data interpretation and manuscript editing.

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Chater 1: Introduction

1.1 Human Alteration of Nitrogen Cycle and Its Impacts

Nitrogen Cycle

Nitrogen is one of the essential elements required by all organisms to constitute proteins, many vitamins, nucleic acids, hormones and enzymes (Mensinga *et al.*, 2003). It is one of the elements in biogeochemical cycle, moving constantly through atmosphere, water, soil, sediments, and living organisms within ecosystems and in the biosphere (Galloway *et al.*, 2004; Vitousek *et al.*, 1997a). Nitrogen that composes 78% of the volume of the atmosphere is in the form of nitrogen gas (N_2), which is chemically unreactive. N_2 requires natural or synthetic processes to form reactive nitrogen (Nr; defined as all nitrogen species except N_2) that is absorbed or used by organisms (Galloway *et al.*, 1995), and beside lightning, only 82 known diazotrophs and 67 unknown species can fix N_2 to ammonia (NH_3) (Dos Santos *et al.*, 2012). Thus, most ecosystems are nitrogen limited on physiological timescales (Elser *et al.*, 2007; Galloway *et al.*, 1995; Vitousek and Howarth, 1991), leading biodiversity richness and creating interactions among animals, plants and soil life (Galloway *et al.*, 2014; Vitousek *et al.*, 1997a). Some of the NH_3 is converted to ammonium ions (NH_4^+) and some undergo nitrification by the Rhizobium bacteria to be converted to nitrate ions (NO_3^-), both of which are available for plants to absorb. In addition, plants and microbes also utilize depolymerized nitrogen-containing soil organic matter, such as amino acids, amino sugars, and nucleic acids, in the nitrogen cycle (see Schimel and Bennett, 2004 for detail).

In the natural biogeochemical cycle, Nr is created by biological nitrogen fixation (BNF) and lightning. BNF in terrestrial ecosystems is 58 Tg (= 10^{12} g) N yr^{-1} and lightning is 5 Tg N yr^{-1}. Marine ecosystems fix nitrogen of 140 Tg N yr^{-1} (Fowler *et al*., 2013). Since BNF was approximately in balance with deep sedimentation and the conversion of Nr back to N_2 by denitrification, anaerobic ammonium oxidation (anammox) and other processes in the natural world, there was little redistribution of nitrogen and little accumulation of Nr (Galloway *et al.*, 2014).

Human Alteration of Nitrogen Cycle

Humans began to grow crops using manure of domesticated animal about 10,000 years ago and to create new Nr by the cultivation of legumes over 65 centuries ago (Galloway *et al.*, 2013). At the end of the 19th century and the beginning of the 20th century, farmers also used other natural sources of nitrogen fertilizers, including guano and mineral nitrate deposits (Galloway and Cowling, 2002). In 1913, based on Frits Haber's invention of a catalytic high-pressure process on synthesis of ammonia from hydrogen and nitrogen (Haber and Le Rossignol, 1908; Haber and van Oordt, 1905; Haber, 2002), Carl Bosch scaled up the process, now called Haber-Bosch process, into plant level (Bosch, 1932; Smil, 2004). However, since this discovery was motivated to develop munitions, it was not until 1950s, that production of synthetic fertilizers for food production started to expand rapidly. At the end of 20th century, more than 40% of the world's dietary protein derives from the Haber-Bosch fertilizer (Smil, 2002). Two thousand years ago, the world population was about 0.2 billion people, creating ca. 3 Tg N yr^{-1} by legume cultivation (Galloway *et al.*, 2013). In 2010, the world population is about 7 billion and about 210 Tg N yr^{-1}, more than the amount supplied by natural process (203 Tg N yr^{-1}), is created by legume cultivation (60 Tg N yr^{-1}), fossil fuel combustion (30 Tg N yr^{-1}), and Haber-Bosh process (120 Tg N yr^{-1}) (Fowler *et al.*, 2013). Detailed fluxes of the altered global nitrogen cycle are shown in Sutton *et al.* (2013a).

On per-capita basis, the anthropogenic Nr creation was constant at ca. 12 kg N yr^{-1} 1850–1950 (Galloway *et al.*, 2014). The creation increased roughly proportional to the population over the period. During 1950 to around 1980, the creation rose to ca. 30 kg N cap^{-1} yr^{-1} in 1980 and the total creation increased dramatically also with the population growth, because of the increasing use of fossil fuel energy and increased use of Haber–Bosch fertilizer with a decreasing use efficiency to meet the demand of higher quality food, especially animal protein. Approximately after 1980 until now, Nr creation has been consistent at ca. 30 kg N cap^{-1} yr^{-1} on per-capita basis and increasing in total.

In 1980, developed countries (including transition economies) consumed around 70% of the global total fertilizers. In 2010, however, the developing economies consume 70% (Sutton *et al.*, 2013a). The emissions from fossil fuel combustion has been decreased by efficient nitrogen oxides (NO_x) controls in many developed countries and fertilizer use and waste has been decreased in Eastern Europe as a results of the economic reforms. On the contrary, fertilizer use for the production of corn for biofuel and of meat has been drastically increased in many developing countries (see Galloway *et al.*, 2014 for detail). Although many areas have too much nitrogen, some areas, mainly in Africa, have too little nitrogen. In Sub-Saharan Africa, annual inputs is around 10 kg ha^{-1}, whereas over 400 kg ha^{-1} for 2010/11 in East Asia (for further details on too much and too little nitrogen in different regions see Sutton *et al.*, 2013a). The rise in international trade of food and feed is an important driver of human alteration of the global nitrogen cycle (Burke *et al.*, 2009;

Galloway *et al.*, 2007; Grote *et al.*, 2005; Lassaletta *et al.*, 2014; Swaney *et al.*, 2012). Inter-regional trade and decoupling of crop and livestock systems generally produces more environmental Nr losses (Billen *et al.*, 2015, 2014; Naylor *et al.*, 2005).

Although an increase in Nr efficiency on a per capita basis is projected (Galloway *et al.*, 2014), population growth to 9.1 billion and increasing demand on animal-based food accompanied by increasing share of house-hold waste are expected to rise anthropogenic Nr creation to 102–156% of the 2010 value, in the order of 232 Tg N yr^{-1} (Bodirsky *et al.*, 2014). The resultant nitrogen release to environment is also projected to increase (Eickhout *et al.*, 2006). The level of current human effects upon the nitrogen cycle is far beyond the plant's safe operating space (Rockström *et al.*, 2009). The planetary boundary for introduction of new Nr is currently estimated to be 62–82 Tg N yr^{-1}, but regional distribution of fertilizer Nr is crucial for impacts (de Vries *et al.*, 2013; Steffen *et al.*, 2015).

Impacts of Excess Reactive Nitrogen

Only 4–15% of Nr used for food production eventually reach humans (Galloway and Cowling, 2002), and the rest is released to the atmosphere, water and soil as "virtual nitrogen" (Galloway *et al.*, 2007). Nitrogen in food is then discharged to surface water in sewage effluent. The use of fossil fuels for energy production has also led the exsess Nr, mainly nitric oxide (NO) and nitrogen dioxide (NO_2) as by product of combustion, in the environment. The accumulation and redistribution of human-induced Nr has contributed to a cascade of environmental, human health and climate impacts (Galloway *et al.*, 2003).

Nr, mainly NO_3^-, in run-off and leaching into surface water contribute to eutrophication and contamination in aquifers and drinking water (e.g. Camargo and Alonso, 2006; Heisler *et al.*, 2008; Selman *et al.*, 2008; Sutton *et al.*, 2013a). Nitrate and nitrite contamination of drinking water and food can lead to infant methaemoglobinaemia, known as blue baby syndrome and cancers of digestive tract (Bryan and Ivy, 2015; Hmelak Gorenjak and Cencič, 2013; Powlson *et al.*, 2008). Severe eutrophication can result in coastal and freshwater dead zones, fish kills, hypoxia and harmful algal blooms. There are over 500 known dead zones in the world in 2014 and the number is increasing from 150 in 2003 (UNEP, 2014). Impacts of eutrophication and oxygen depletion to aquatic ecosystems can be more severe on coral reefs, sea grass beds, wild or farmed fish and shellfish (see Erisman *et al.*, 2013 for further details).

Some Nr goes to the atmosphere by denitrification, contributing the emissions of nitrous oxide (N_2O) (Erisman *et al.*, 2013). N_2O is both strong greenhouse gas and important substance that deplete ozone in the stratosphere, (Ravishankara *et al.*, 2009).

N_2O emissions and forming of ground-level ozone lead by NO_x emissions have warming effect on climate, whereas Nr emissions also has cooling effect by contributing to reducing the atmospheric life-time of methane, forming particulate matters, and increasing the growth of plants (Butterbach-Bahl *et al.*, 2011; Galloway *et al.*, 2013). Erisman *et al.* (2011) estimate net cooling effect of Nr emissions on climate with very high uncertainty.

Anthropogenic emissions of NO_x to air are primarily due to combustion (Galloway *et al.*, 1995). NO_2 is an irritant gas and high NO_2 levels can cause severe damage to the lungs and can also induce a variety of respiratory illnesses (Sutton *et al.*, 2013a). Long-term NO_2 exposure may reduce lung function and raise the risk of respiratory symptoms (WHO, 2003). NO_x can increase concentration of ground-level (tropospheric) ozone (Chameides *et al.*, 1994), other photochemical oxidants and secondary organic aerosol particles, leading atmospheric visibility decrease and acidic deposition on land, surface waters, or other surfaces (Galloway *et al.*, 2003). Exposure of ozone can initiate and exacerbate reactive airways disease (RAD), coughs, and asthma (Townsend *et al.*, 2003), and also increase mortality and respiratory morbidity rates (Amann *et al.*, 2008). The impact of ozone on agricultural crop is also estimated to be relative yield losses of 3–16% depending of types of crops and metrics (Van Dingenen *et al.*, 2009).

Anthropogenic NH_3 emissions to the air is mainly from agricultural and livestock production systems, and partly from biomass burning, industrial and various waste sources (Sutton *et al.*, 2013b). The emitted NH_3 is either deposited or transformed into ammonium aerosol, contributing to fine particulate matter and regional haze concentrations, and subsequent deposition (Galloway *et al.*, 2003). While human alteration of nitrogen cycle is not always the cause of fine particulates, emissions of NO_x and NH_3 are important drivers of fine particulate air pollution worldwide (Townsend *et al.*, 2003). Particulate matter is a large contributor to cardiovascular diseases, respiratory diseases, asthma, reduced lung function, and overall mortality, leading a loss of statistical life expectancy of six to 12 months across most of central Europe (Moldanová *et al.*, 2011; Townsend *et al.*, 2003; WHO Regional Office for Europe, 2006).

Nitrogen wet and dry deposition has also been increased by human-induced Nr emissions (Fowler *et al.*, 2013), contributing to soil acidification and forest dieback (van Breemen *et al.*, 1982). Additionally, excess Nr can cause biodiversity loss due to competition between nitrogen-philic and nitrogen-phobic species (Galloway *et al.*, 2013). Atmospheric nitrogen deposition exceeds 10 kg ha^{-1} yr^{-1} in 40% of protected areas and is projected to continue in 2030 (Bleeker *et al.*, 2011). High rate of nitrogen deposition have the largest impact on biodiversity in temperate forests, boreal forests, arctic, and alpine, where biomes are most nitrogen-limited (Dise *et al.*, 2011; Sala *et al.*, 2000).

The excess Nr input can also lead to soil acidification in agricultural ecosystems with high rates of fertilization (Guo *et al.*, 2010). While this may be mitigated by lime addition in agroecosystems, essential soil bases in natural soils are tend to be leached out, while toxic metals are mobilized, which lead to further risks for forest health and freshwater fish populations (Sutton *et al.*, 2013a). On the other hand, without synthesized fertilizer use and intensification of crop and livestock farming associated with Green Revolution, a similar increase in agricultural area would have been needed to meet the increased demand of food, especially of meat, and thus would have caused further disturbance on virgin ecosystems (de Vries *et al.*, 2013).

Current Policies and International Partnerships

The current policies are tend to be fragmented to address individual Nr species from specific source sectors (agriculture, transport, industry, waste, etc.) and media (air, freshwater, marine), and for specific issues (food supply, health, trade, water and air quality, climate change, biodiversity, etc.)(Sutton *et al.*, 2013a, 2011a). Existing nitrogen policies have made much progress in sectors consisting of few major actors (e.g. electricity generation, car manufacturing, municipal water treatment), but have achieved lower emission reduction when involving many diverse actors (e.g. citizens' transport choices, farmer practices), which indicates needs for long-term dialogue, education and training (Sutton *et al.*, 2013a).

Policy implementation that reflects the integrated actions to address air, water and soil pollution resulting from Nr emissions have been most successful (UNEP and WHRC, 2007). In Europe, progressive efforts have been made regarding Nr and its role in air and water pollution. The Convention on Long-Range Transboundary Air Pollution and its Protocols have reinforced environmental protection over time considering additional information. Guidelines implemented under the Helsinki Commission in 1974 cover a range of pollutants and have been reinforced as more is recognized as the causes and impacts of eutrophication in the Baltic Sea. In North America, continuing restoration of the Chesapeake Bay through an intragovernmental, interagency approach underlines the role of a regional governance framework for managing Nr in achieving coordination and the necessary joint actions among governmental agencies with overlapping jurisdictions. However, neither of the examples have reduced levels of Nr to acceptable levels (see summaries of other policy responses in Galloway *et al.*, 2013; Sutton *et al.*, 2013a; UNEP and WHRC, 2007; Winiwarter *et al.*, 2015).

There are ongoing efforts towards integrated management of nitrogen. A global network of scientists, the International Nitrogen Initiative (INI; http://www.initrogen.org), was established and sponsored by the Scientific Committee on Problems of the Environment (SCOPE) and the International Geosphere-Biosphere Programme (IGBP) in 2003. Major headway has been made making integrated assessments of the human impacts and possible policy responses on the nitrogen cycle (Galloway *et al.*, 2013). The *European Nitrogen Assessment* (ENA) (Sutton *et al.*, 2011b) provided the most comprehensive cost-benefit assessment (Brink *et al.*, 2011) to date (Sutton *et al.*, 2013a) and ENA is a contribution to the work of the INI European Centre. The assessment on Nr in the USA has been also reported by the EPA Science Advisory Board (US EPA, 2011).

The Global Partnership of Nutrient Management (GPNM) has been launched at the 17th session of the UN Commission on Sustainable Development in 2009. The GPNM is a global partnership of governments, industry, science community, NGOs, UN agencies and various international and regional organizations (GPNM, 2014). The GPNM recommended four main mainsprings as a basis of the nutrient management to focus on "building of a shared interest and agenda among and within countries; stakeholder engagement and partnerships and the communication and mainstreaming of best practice tools and integrated approaches to guide cost effective decision making" (Tompkins and Erisman, 2010). The GPNM prepared the global overview, "Our Nutrient World: the challenge to produce more food and energy with less pollution" (Sutton *et al.*, 2013a), of the nutrient management practices and policies in collaboration with the INI.

Addressing the impacts of excess Nr, especially severe impacts on marine environment by "marine pollution, including … nitrogen-based compounds, from a number of marine and land-based sources, including shipping and land run-off", the global leaders at the Rio+20 Summit in 2012 committed to "promote, enhance and support more sustainable agriculture … while conserving land, water, … biodiversity and ecosystems". It lead to Goal 14 (Conserve and sustainably use the oceans, seas and marine resources) of the Sustainable Development Goals (SDGs) included to target the reduction of marine pollution from land-based sources of nutrients, i.e. nitrogen and phosphorus.

From 2015, funded by the Global Environment Facility (GEF) Trust Fund, and implemented by the United Nations Environment Programme (UNEP), an initiative called "Towards International Nitrogen Management System (INMS)" has started a research project for improving understanding of the global nitrogen cycle towards the establishment of an INMS. It is executed through the United Kingdom Natural Environment Research Council (NERC), and its Centre for Ecology & Hydrology (CEH), based in Edinburgh, on behalf of the INI. INMS is an international science-policy support process aiming to support governments and others for addressing better management across the nitrogen cycle by integrating people, information, approaches, indicators, cost-benefit analysis, regional demonstration, etc. and to contributes to improvement of macro-economic nitrogen use efficiency, while reducing surplus that can cause pollution (Towards INMS, 2015).

1.2 Footprint Indicators for Quantifying the Consumption-based Emissions

Concept of Footprint and Footprint Studies

The ecological footprint (EF) is an consumption-based indicator that measures the amount of land and water required to meet the demand of human, developed by William E. Rees and Mathis Wackernagel in early 1990s (Rees, 1992; Wackernagel and Rees, 1996). It compares the amount of the biologically productive land and sea area to produce the renewable resources consumed and to assimilate the waste generated (EF of the demand) with the available amount of land and sea area (biocapacity of the demand) and assess the sustainability of a given population's lifestyle. The EF is composed of built-up land, carbon uptake land, cropland, grazing land, forest land and fishing ground. The EF introduced a concept of consumption-based account and accessing consumption on renewable natural resources.

The idea of "footprint" has been extended to different types of burdens and impacts on global sustainability, as a quantitative measurement describing the appropriation of natural resources by humans (Čuček *et al.*, 2012). However, conversions of the burdens and impacts into area units requires assumptions that would increase the uncertainties and errors of footprints calculation (e.g. Bastianoni *et al.*, 2012; Venetoulis and Talberth, 2007; Wiedmann and Minx, 2008). The conversion factors for the EF are determined by the Global Footprint Network (GFN), which offers the standard method for the calculation. Reflecting the issue, only composite footprints (EF and its categories, the Sustainable Process Index and the Sustainable Environmental Performance Indicator) are defined in units of area, and other footprints are not usually defined (only) in area units (Čuček *et al.*, 2012).

Following the EF, the water footprint (WF) was developed in 2002 by Hoekstra and Hung (Hoekstra and Hung, 2002). It describes the total volume of direct and indirect (virtual) fresh water used by a process, product, company or sector and includes water consumption and pollution throughout the full production cycle from the supply chain to the end-user. The carbon footprint was evolved from the life cycle impact category indicator, the global warming potential (GWP) (Finkbeiner, 2009), and it is first defined in scientific literature in 2003 by Høgevold (Høgevold, 2011). The carbon footprint is usually defined as the amount of CO_2 and other GHGs emitted through all stages of its life cycle, converting the other GHGs in the unit of CO_2 by the GWP, but the calculation method is not yet standardised (Čuček *et al.*, 2012; Wiedmann and Minx, 2008).

It has been widely acknowledged that no single aggregated indicator is neither able to comprehensively monitor human impacts on the environment nor provide the meaningful information in detail, but indicators need to be used and interpreted jointly (Fang *et al.*, 2014; Galli *et al.*, 2012; Wiedmann and Barrett, 2010). To complement the widely-known three footprints, a continuously expanding list of other footprints has been developed, including nitrogen footprint (NF; see Section 1.3), energy footprints, land footprints, biodiversity footprint (Lenzen *et al.*, 2012), material footprint (Wiedmann *et al.*, 2015), social footprints including employment footprint (Alsamawi *et al.*, 2014), economic footprints, and combined footprints (see Čuček *et al.*, 2012 for detail).

Top-Down Approach and Bottom-Up Approach

Two types of approaches have been applied to calculate environmental footprints in the literature: bottom-up and top-down approaches. Bottom-up approach refers to both a process-based life cycle analysis (LCA), which uses detailed descriptions of individual production processes and a coefficient analysis based on analyses of individual production processes. Examples of process-based LCA include EF for various products (Huijbregts *et al.*, 2008) and WF for specific pasta sauce and peanut chocolate candies (Ridoutt and Pfister, 2010). Besides common LCA analysis on a product, some studies used ratios of footprint per physical unit of consumption, e.g. WF for cotton products (Chapagain *et al.*, 2006) and energy footprints for different bioethanol production processes from sugar beet (Šantek *et al.*, 2010). The standardized methods of EF (known as the National Footprint Accounts, NFA; Borucke *et al.*, 2013) and WF (Hoekstra *et al.*, 2011), and the existing method for food-related NF (Leach *et al.*, 2012) use the sum of all the products consumed in a country (domestic production minus export plus import). The data mainly used for the calculations are, based on production data for NFA and production process-based factors and consumption data for the WF and food-related NF. Those analyses of EF and WF and an application of NF (Shibata *et al*., 2014) consider trade by physical bilateral flows. The advantages of bottom-up approach are simplicity for understanding and sensitivity for accessing difference in product level, resulting in a wide use in practical business. However, this approach does not trace the entire industrial supply chain, leading to inter-sectoral cut-off and inter-regional cut-off (see Feng *et al.*, 2011; Tukker and Jansen, 2006 for further detail).

Top-down approach refers to both a mass balance analysis based on national statistics (e.g. Gu *et al.*, 2013) and an economic input–output (IO) analysis. Economic IO analyses apply hierarchical models with total factor multipliers based on national economies to determine embodied effects per unit of production (Lenzen, 2008a). The calculation starts from the total domestic emissions (or use of resources) usually divided by monetary unit. The consumption is defined as total domestic emissions minus emissions for the exported products plus the gross indirect emissions for the imported products. The advantages of the approach are comprehensiveness for its coverage and capability for tracing the entire supply chains, commonly used in analyses on the national and supra-national level. Single-region input–output (SRIO) analysis (e.g. Guan and Hubacek, 2007; Limmeechokchai and Suksuntornsiri, 2007) can capture inter-sectoral cut-off, and multi-region input–output (MRIO) analysis (e.g. Lenzen *et al.*, 2012; Peters *et al.*, 2011; Turner *et al.*, 2007; Wiedmann *et al.*, 2015; Yu *et al.*, 2010) can capture both inter-sectoral cut-off and inter-regional cut-off. However, these methods are limited by the numbers of sectors in the IO database used, in analysing detailed consumption (Feng *et al*., 2011).

Hybrid methods, combining the two approach, can be taken, but it requires careful consideration on the frameworks to avoid double counting (Lenzen, 2009, 2008b; Strømman *et al.*, 2009; Suh, 2004) The existing method for energy-related NF applies SRIO approach, but to gain high resolution on commodities used, it complements the results by bottom-up approach (e.g. for the use of car and electricity at household level) using activity data and emission factors (Leach *et al*., 2012).

1.3 Nitrogen Footprint Analyses

N-calculator Approach and Related Tools

The NF concept has been introduced as a tool called to "N-calculator" to communicate the scientific findings on nitrogen issues to all the stakeholders (Leach *et al.*, 2012; N-Print, 2011). The NF provided quantitative estimates of consumers' contributions to the nitrogen issues, and was defined as "the total amount of Nr released to the environment as a result of an entity's resource consumption, expressed in total units of Nr" (Leach *et al.*, 2012).

The N-calculator method is to calculate the NF for an individual by multiplying the ratio of a person's consumption to the average person in a country (Leach *et al.*, 2012). In the following literature of NF, discussion focused on the NF for average person as the per-capita NF for a country. The NF is composed of food NF and energy NF. For both of the NF component, it assumes a closed country. Food NF is Nr derived from nitrogen fertilizer and crop-fixed nitrogen. Food NF is the sum of two parts: food production and food consumption. Food production NF is determined as nitrogen consumption multiplied by virtual nitrogen factors (VNFs), which indicate the amount of Nr released to the environment during production per unit of nitrogen consumed. VNFs for each food category are calculated using a flow-based model with factors for efficiency, recycling, etc. Fish and seafood are categorised in a single category and calculated in the same method as livestock, despite the diversity within seafood products and the share in the total protein intake (6.4%) and in the animal protein intake (15%) similar to that of poultry meat (FAO, 2014). Food consumption NF is the nitrogen consumption subtracted by the average rate of denitrification in sewage treatment. The nitrogen consumption is estimated using FAOSTAT food protein supply data. Energy NF is Nr derived from combustion of fossil fuels. Energy NF was calculated by a national level SRIO analysis, using the economic IO tables for each country provided by Organization for Economic Cooperation and Development (OECD).

The N-calculator method has been applied to individuals, institutions (Leach *et al.*, 2013), food labels (Galloway *et al.*, 2014), and extended to Nr emissions neutrality to implement off-sets (Leip *et al.*, 2014). The N-Loss indicator has also been introduced to represent the territorial Nr emissions for different regions of the world as a result of the production and consumption of food and the use of energy, being included as one of the related indicators to the Aichi Target 8 on the reduction of pollution including from excess nutrients in the context of the Convention on Biological Diversity (Galloway *et al.*, 2014).

All of these analyses are towards the integrated nitrogen management, involving various stakeholders.

NFs for countries on per capita basis

The N-calculator method were applied to the USA and the Netherlands for the first time (Leach *et al*., 2012). The calculated VNFs for food categories showed that beef has much higher impact than poultry meat for the same protein consumption. The findings showed that our lifestyle choices, especially our food choices, have major impacts on the Nr release to the environment. Applying the country-specific VNFs, the N-calculator method have calculated the per-capita NFs for Germany (Stevens *et al*., 2014), the United Kingdom (UK) (Stevens *et al*., 2014), Japan (Shibata *et al*., 2014), Austria (Pierer *et al*., 2014), Portugal and Tanzania (Galloway *et al*., 2014). The per-capita NF for China was calculated using mass balance methods (32 kg cap^{-1} yr^{-1}; Gu *et al*., 2013). The results demonstrated the great difference between developed countries and a developing country, such as Tanzania. Food was found to be over-consumed in most of the countries ("food consumption" in Table 1.1), compared with the recommended level of 2.5–3.5 kg cap^{-1} yr^{-1} (based on the World Health Organization (WHO) and United States Department of Agriculture (USDA) dietary recommendation), suggesting a decrease in protein consumption as an option to

Table 1.1 Annual per-capita nitrogen footprints for eight countries (kg N cap^{-1} yr^{-1}) calculated using the N-Calculator from Galloway *et al*. (2014).

	USA	NL	Germany	UK	Japan	Austria	Portugal	Tanzania
Food consumption, released	5.0	1.1	1.6	4.9	3.4	1.1	6.0	2.0
Food production	22	20	18	18	26	16	18	12
Housing	3.0	0.8	1.6	2.0	0.8	0.8	0.7	0.2
Transport	6.0	1.1	1.8	1.1	0.7	1.6	3.5	0.8
Goods and Services	2.5	0.5	0.7	1.1	1.0	0.6	0.5	0.2
Total	39	23	24	27	32	20	29	15
Sewage, % denitrification	5%	78%	67%	2%	33%	79%	0%	0%
Food consumption	5.3	5.0	4.9	5.0	5.1	5.2	6.0	2.0

"Food consumption" refers to the nitrogen actually consumed and subsequently excreted, whereas "food consumption, released" refers to the nitrogen released to the environment after sewage treatment.

reduce one's NF. The food consumption NFs ("Food consumption, released" in Table 1.1) are, however, low in the Netehrlands, Germany and the UK, where advanced (tirtially) sewage treatment that converts Nr to N_2 is widely introduced. The other reduction options are imporovement of nitrogen use efficiency in production processes and lessening food waste.

The remaining challenges are, to extend the NF analysis to the global level including international trade, to link Nr emissions information to the final consumers who induced the emissions with spatial information, to differentiate the forms of Nr emissions, and to make the model sensitive to a variety of diets, including plant and seafood-based diets.

1.4 Objectives and Overview of Dissertation

Given the urgent needs to achieve significant reduction in Nr emissions by global integrated nitrogen management, further improvement of the communication tools for nitrogen is essential. To this end, this study focuses first on the global analysis of NF to observe the current global situation from the NF perspective, moves on the investigation on NF of fish and seafood to obtain the basis for sustainable food choices, and then examine the options for sustainable diets to guide consumers' engagement.

The global analysis of NF is performed in Chapter 2, aiming (1) to develop a novel global NF model for all nations and (2) to explore the global picture of the NFs and the role of international trade on it. Based on findings of the previous studies suggesting food choices, especially meat consumption, and wealth as key drivers, the author proposes hypotheses as follows:

1. Developed countries pollute agricultural countries through their consumption;
2. Agricultural and energy-intensive products are globally the key commodities for NFs.

The investigation on NF of fish and seafood is carried out in Chapter 3, aiming (3) to develop an improved NF model for calculating NF of seafood production and consumption and (4) to provide more comprehensive and detailed information on food choices for reducing reactive nitrogen (Nr) emissions. Since the previous studies showed the substantial differences between NFs of beef and poultry meat, whereas a simple method similar to livestock to calculate NF of seafood was applied, the author proposes hypotheses as follows:

3. Calculating NF of seafood requires a different approach from the approach for livestock.

4. Different types of seafood have diverse NFs per unit of protein.

Further discussion on the findings of the previous chapters and a case study on sustainable diets are implemented in Chapter 4 in order to provide more comprehensive and detailed information for policy makers and consumers on their food choices to reduce their NFs

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Chater 2: Substantial nitrogen pollution embedded in international trade

2.1 Summary

Anthropogenic emissions of reactive nitrogen to the atmosphere and water bodies can damage human health and ecosystems (Erisman *et al.*, 2013; Sutton *et al.*, 2011b). As a measure of a nation's contribution to this potential damage, a country's nitrogen footprint has been defined as the quantity of reactive nitrogen emitted during the production, consumption and transportation of commodities consumed within that country, whether those commodities are produced domestically or internationally (Leach *et al.*, 2012). Here we use global emissions databases (FAOSTAT, 2015; Heffer, 2013), a global nitrogen cycle model (IPCC, 2006), and a global input–output database of domestic and international trade (Lenzen *et al.*, 2013b, 2012a) to calculate the nitrogen footprints for 188 countries as the sum of emissions of ammonia, nitrogen oxides and nitrous oxide to the atmosphere, and of nitrogen potentially exportable to water bodies. Per-capita footprints range from under 7 kg N yr^{-1} in some developing countries to over 100 kg N yr^{-1} in some wealthy nations. Consumption in China, India, the USA and Brazil is responsible for 46% of global emissions. Roughly a quarter of the global nitrogen footprint is from commodities that were traded across country borders. The main net exporters have significant agricultural, food and textile exports, and are often developing countries, whereas important net importers are almost exclusively developed economies. We conclude that substantial local nitrogen pollution is driven by demand from consumers in other countries.

2.2 Introduction

Humans are transforming the global nitrogen cycle by creating more reactive nitrogen (Nr; all species except N_2) than is naturally fixed (Fowler *et al.*, 2013). Fertilizer use and fuel combustion cause Nr emissions that seriously damage human health and ecosystems (Sutton *et al.*, 2013, 2011a, 2011b). Facing drastic increase in fertilizer use to feed an ever-growing world population exhibiting increasing preference for animal products (Bodirsky *et al.*, 2014; Galloway and Cowling, 2002), urgent action is requested by Rio+20-summit leaders (UNGA, 2012).

As one of the tools for integrated nitrogen management, the nitrogen footprint (NF) concept has been developed to provide quantitative estimates of consumers' contributions to the problem (Leach *et al*., 2012). It has also been applied to institutions and extended to nitrogen emissions neutrality and the overall nitrogen use of nations (Galloway *et al*., 2014; Gu *et al*., 2013b; Leach *et al*., 2013; Leip *et al*., 2014). Per-capita NFs have been calculated for the United States of America (USA), the Netherlands, Germany, the United Kingdom (UK), Japan, and Austria (Leach *et al*., 2012; Pierer *et al*., 2014; Shibata *et al*., 2014; Stevens *et al*., 2014), using the N-calculator tool, and for China, using mass balance methods (Gu *et al*., 2013b); however, with incomplete information about their global origin. In these analyses, food was found to be the most dominant component and differences in diet between countries and scenarios cause substantial differences in per-capita NFs. For example, reducing food protein consumption to the recommended level (Joint WHO/FAO/UNU Expert Consultation, 2007) reduces the NF of food and energy by 33% in the UK (Stevens *et al*., 2014). Assuming that food is entirely produced within Japan, Shibata *et al.* (2014) calculated the total NF of Japan to be 37.0 kg cap^{-1} of Nr per year, however after relaxing this assumption by simulating food imports as coming from the USA, the resulting NF decreased by 24%. At the time of writing, there were no further NF studies that considered both direct and indirect impact through international trade.

Only some analyses on the international trade of nitrogen as a constituent of the traded product indicate that the globalization of previously localized agricultural production and consumption is increasing nitrogen impacts (Billen *et al*., 2015; Lassaletta *et al*., 2014), with regions producing nitrogen-rich products bearing the environmental cost of their exports (Burke *et al*., 2009; Galloway *et al*., 2008; Lassaletta *et al*., 2014). Investigations of direct impacts through international trade have shown that regions producing nitrogen-rich products such as meat and soybeans for feed (e.g. Brazil) bear the environmental cost of production to supply the consumers (e.g. China) (Galloway *et al*., 2008; Lassaletta *et al*., 2014; Naylor *et al*., 2005). Burke *et al.* (2009) investigated embodied nitrogen emissions as the environmental impacts of meat production and consumption between four countries (Brazil, the USA, the Netherlands, and Japan) and their trading partners. Their findings showed that more than half of the exports of embodied nitrogen from the USA were destined for China, Mexico, Japan, and the European Union, but this trend was not true in terms of water footprints because little water is embodied in feed, animal, or meat products. Lassaletta *et al.* (2014) investigated bilateral trade of nitrogen in food and feed around the world for 50 years and the movement of nitrogen among 12 world regions. They found that the internatinally-traded nitrogen has increased significantly and now concerns one-third of the total nitrogen in crop production. Furthermore, it is explained that this rise is largely due to an increase in the share of animal protein in the human diet as well as population growth (Billen *et al.*, 2015; Lassaletta *et al.*, 2014). They emphasised the need to make changes to the consumption patterns together with cleaner production in order to reduce nitrogen pollution. Wier and Hasler (1999) developed an input–output model to integrate nitrogen emissions from agriculture, industries, and household in Denmark, highlighting agriculture as a key sector. To date, however, relationships between nitrogen emissions embodied in exported goods and final consumers are not fully understood globally, despite the fact that an inter-convention agreement on nitrogen has been suggested as a powerful mechanism for integrated nitrogen management (Sutton *et al.*, 2011b). For reducing nitrogen emissions globally, two aspects must be considered. First, the spatial distribution of the threats is not equal, and likely to be denser in developing countries (Galloway *et al.*, 2004; Gruber and Galloway, 2008). Second, whilst Nr changes its form as it moves between ecosystems (Galloway *et al.*, 2003; Schlesinger, 2009; Vitousek *et al.*, 1997b), policies and countermeasures have mainly dealt with the issue for only a single form of Nr, or for isolated industry sectors in particular countries (Erisman *et al.*, 2003; Sutton *et al.*, 2011b; UNEP, 2012).

Environmentally extended multi-region input–output (MRIO) analysis has been applied at the global scale to quantify nations' footprints (Andrew and Peters, 2013; Feng *et al.*, 2011; Hertwich and Peters, 2009; Lenzen *et al.*, 2013a, 2012b; Peters *et al.*, 2012). The analysis of carbon footprints of nations by Peters *et al.* (2012) demonstrated that a significant fraction of emissions produced in emerging markets (e.g. China and India) are embodied in exported goods to developed regions (e.g. the USA, Japan and the EU27). Lenzen *et al.* (2012b) explained that 30% of global species threats are caused by international trade. Comparing analyses of individual production processes (bottom-up approach) and economic analysis (top-down approaches), the latter including environmentally extended MRIO and bilateral trade flow analysis, Feng *et al.* (2011) concluded that "top-down approaches have a comprehensive system boundary that allows tracing whole industry supply chain effects", and showed that many developed countries are net importing countries. Galli *et al.* (2012) suggested integrating nitrogen emissions into existing footprinting approaches within environmentally extended MRIO analysis as a set of indicators, "Footprint Family", to deal with diverse environmental impacts arising from food production.

To date, a systematic and comprehensive, spatially explicit NF assessment for the entire world does not exist. Our study is the first to trace the flow of different forms of Nr emissions along international trade routes from hotspots of nitrogen pollution to centres of consumption, using a global trade database for 188 countries and almost 15,000 economic sectors (see Appendix 1.1.1 and Tables A.1 and A.2 for basic of methods).

2.3 Methods

Summary

We connect the IPCC's model for the global nitrogen cycle (IPCC, 2006) with data on emissions of all forms of Nr sourced from the UN's Food and Agriculture Organisation (FAOSTAT, 2015) and the International Fertilizer Industry Association (IFA; Heffer, 2013) to generate a complete compendium of emissions of four nitrogen compounds, for 188 world countries and regions with a combined number of almost 15,000 industry sectors (see Figures 2.1 and 2.2 and Tables 2.1, 2.2, A.3 and A.4 for the detail; China and Hong Kong are considered independent entities in this work). More specifically, after aligning detailed FAO and IFA data for crop and livestock categories, we employ the IPCC's nitrogen model to arrive at emissions by compound by FAO/IFA category, which we then convert into the MRIO classification and integrate with auxiliary data on NO_x (NO and NO_2), NH_3, and N_2O emissions to air (Kanemoto *et al.*, 2014). We then estimate the direct Nr emissions to water from household sewage. These steps yield a so-called *satellite account* in terms of Nr emissions, containing entries in units of Gg (=10^9 g) nitrogen for individual industry sectors in 188 countries. We combine the nitrogen satellite account with a MRIO database (Lenzen *et al.*, 2013b, 2012a) and use both as an input into a generalized input–output analysis (Leontief, 1970). The satellite account is docked onto an MRIO table, and the entire system is inverted to yield so-called nitrogen *multipliers*. These multipliers describe the amount of Nr emissions required directly and indirectly through the entire global supply-chain network, to produce commodities consumed by final consumers such as households. Summing up nitrogen contributions from all commodities consumed in any particular country yields that country's *NF* on country basis. From this country's NF, we calculate per-capita NF for the country and its net Nr emissions through international trade (for the results shown in Figures 2.3–2.5). We dissect the aggregated footprint results into individual components describing the flow of embodied Nr along particular international trade routes, using SPA (see Sections 2.3.2–2.3.5 for further details).

Converting the satellite into multipliers follows the same method as used for the quantification of the biodiversity footprint in a previous issue of *Nature* (Lenzen *et al.*, 2012b).

2.3.1 Calculation for nitrogen footprint of nations

Overview

Our production NF calculation consists of five parts; (1) collecting detailed data for crop/livestock, (2) calculating nitrogen emissions, (3) converting classifications, (4) integrating the two sets of nitrogen emissions data, and (5) performing an extended input–output analysis (Figure 2.1). We also calculate consumption NF and sum up NF of both production and consumption as total NF.

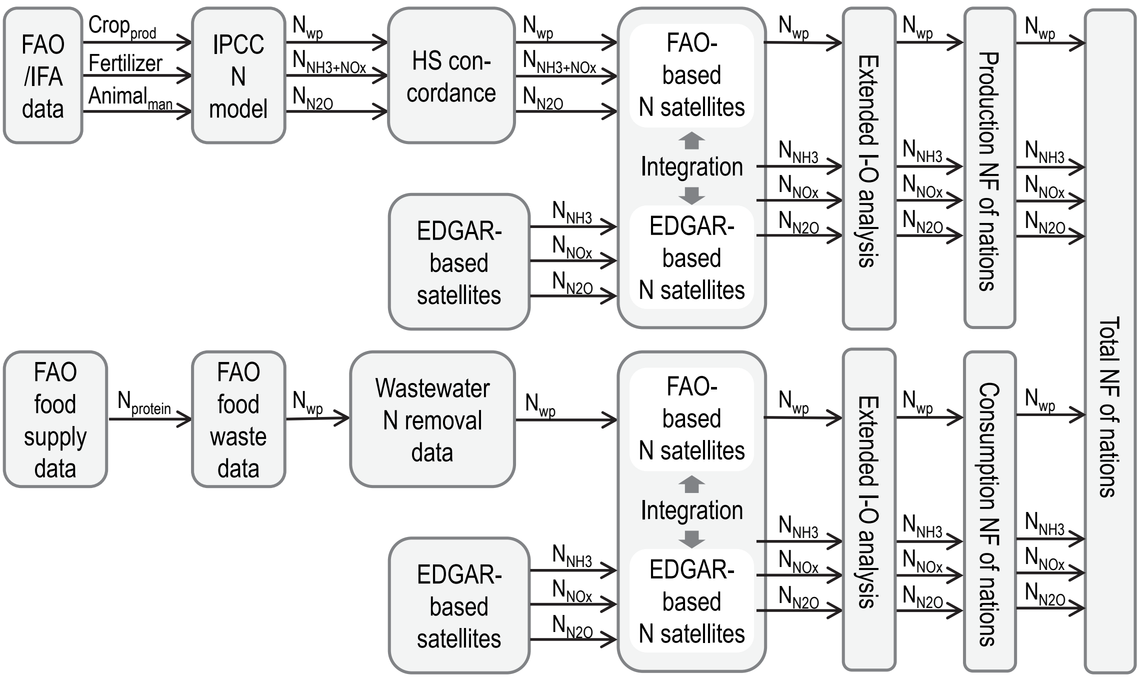

Figure 2.1 Simplified flow chart of our nitrogen footprint calculation. Starting from FAO crop production-related data (Crop$_{prod}$) and livestock manure-included nitrogen data (Animal$_{man}$; FAOSTAT, 2015), as well as IFA fertilizer data (Fertilizer; Heffer, 2013), we a) calculated the nitrogen potentially exportable to water bodies (N_{wp}), the emissions to air of ammonia and nitrogen oxides ($N_{NH3+NOx}$), and emissions of nitrous oxide (N_{N2O}) using IPCC nitrogen emission equations (IPCC N model; IPCC, 2006), b) converted FAO data into MRIO classification, c) integrated the resulting FAO-based nitrogen (N) satellites with updated EDGAR-based air emission data (from Kanemoto *et al.*, 2014), and d) performed an extended

input–output analysis to calculate the nitrogen footprints (NFs) of production. We also calculated the consumption NFPs of nations. To this end, we a') calculated supplied food protein nitrogen ($N_{protein}$) using FAO food supply data, b') multiplied the percentage of food not wasted using FAO food waste data, and c') multiplied the percentage of wastewater nitrogen not removed (from Galloway *et al.*, 2014; OECD, 2013; Stevens *et al.*, 2014; UNEP and WHRC, 2007; Wu, 1999) to calculate N_{wp}. We then integrated the account with consumers' direct emissions from EDGAR-based data to calculate the NFPs of consumption. Finally, we summed up NFP of both production and consumption as total NFP of nations.

Crop/Livestock Data Preparation

To model global nitrogen emissions, we used

- FAO data on production, harvested area and yield for 162 crop types in 216 countries/areas (FAOSTAT, 2015),
- FAOSTAT nitrogen data on manure applied to soil, manure left on pasture, and manure management for 16 livestock types in 217 countries/areas (FAOSTAT, 2015), and
- IFA data on the amount of nitrogen fertilizers applied to 13 crop categories in 28 countries/regions (Heffer, 2013).

Missing area data were inferred by dividing production by yield (FAOSTAT, 2015), using world average yield when the yield data were missing. Fertilizer data (Heffer, 2013) for broader categories and for regions were distributed across more detailed commodities and countries in proportion to harvested area (FAOSTAT, 2015). FAO crop/livestock types, IFA fertilizer categories, the allocation of crop types to fertilizer categories, and data categories of countries/areas are explained in Tables A.3 and A.4.

Calculating Nitrogen Emissions

We used a nitrogen flow model from the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006) to estimate detailed nitrogen emissions to air, as well as the nitrogen emission potential to water. We chose the IPCC model because FAOSTAT uses this method to estimate nitrogen emissions from manure. In accordance with the IPCC, we calculated the total nitrogen emission (N_{all}) as the sum of the nitrogen potentially exportable to water bodies (N_{wp}), nitrogen in NH_3 and NO_x emissions to air ($N_{NH3+NOx}$), and nitrogen in N_2O emissions to air (N_{N2O}); $N_{all} = N_{wp} + N_{NH3+NOx} + N_{N2O}$. N_{wp} includes the nitrogen emissions potential to surface water, and to underground water. Since their main form is common as NO_3^-, we considered them equally from consumer's nitrogen budget perspective. In order to deal with the temporal complexation of the nitrogen cycle (e.g. mineralization, leaching, denitrification, deposition, etc.), we took a snap shot of the time of reporting, and summed up cycle stages stemming from fertilizers (N_{x_fert}) and crop residues (N_{x_res}) for crops, and manure applied to soil (N_{x_soil}), manure left on pasture (N_{x_pstr}), and manure management (N_{x_mgt}) for livestock. Each nitrogen emissions component of chemical form *x* (Nwp, NH_3+NO_x, and N_2O) and cycle stage *y* (fertilizers; crop residues; manure applied to soil; manure left on pasture; and manure management) was calculated as $N_{x\_y} = N_{\_y} \times \alpha_{x,y}$, where $N_{\_y}$ is nitrogen applied to stage *y* of agricultural production (e.g. nitrogen component of fertilizers) and $\alpha_{x,y}$ is the coefficient for chemical form *x* and component *y* (Table 2.1; see Section 2.3.5 for uncertainties). The calculated results are in line with the global nitrogen fluxes shown in Sutton and colleagues (2013).

Table 2.1 Coefficients ($\alpha_{x,y}$) for the N model.

Component	Nwp	NH_3 + NO_x	N_2O
Fertilizers	0.3	0.1	0.01[a] 0.003[b]
Crop residues	0.3	0.2	0.01
Manure applied to soil	0.3	0.2	0.01
Manure left on pasture	0.3	0.2	0.02[c] 0.01[d]
Manure management	0	—[e]	—[f]

Notes: [a]: for all crops except paddy rice; [b]: for paddy rice; [c]: for cattle (dairy, non-dairy and buffalo), poultry and pigs, [d]: for sheep, goats, camels, llamas, horses, mules, and asses; [e]: calculated by "indirect N_2O emission" × 100 × 28/44; [f]: calculated by "direct N_2O emission" × 28/44. Indirect N_2O emission is originally for calculating N_2O emission drived from emissions of NH_3 and NO_x, which equals to 1% of emissions of NH_3 and NO_x.

Bridging FAO and MRIO Classifications

Calculated FAO-based nitrogen emissions data are expressed at a detail of 178 crop and livestock types, which are different to the sector classification of countries as represented in the Eora MRIO database (Lenzen *et al*., 2013b, 2012a). To convert FAO data into the country-specific MRIO data, we needed to provide a bridge between the two classifications. This was done by setting up *concordance matrices* between the 178 FAO classes and each of Eora's countries' sectors. Let **C** be such a concordance matrix, holding $C_{ij} = 1$ if FAO class *i* corresponds to Eora sector *j*, and 0 otherwise. (We constructed a binary 178 × *N* concordance matrix **C** by assigning for each FAO class a value of 1 to those industry sectors in the MRIO database that include the respective FAO class, and 0 otherwise, where N denotes economic sectoral numbers.) **C** cannot be used yet for converting a FAO-classed data vector into a Eora-classed data vector, because the rows of **C** are not normalized (see Supplementary Text S4.2 of Lenzen *et al*. 2012a). Nr emissions from beef and dairy sectors are mostly allocated to one economic sector for each country, except for the countries that have economic sectors for beef and dairy separately, i.e. Australia, Brazil, Israel, Japan, Kenya, Kyrgyzstan, the UK and the USA. A normalized *map* can be calculated from $\mathbf{M} = (\mathbf{C}\widehat{\mathbf{x}_m}\mathbf{1}_m)^{-\mathbf{1}}\mathbf{C}\widehat{\mathbf{x}_m}$, where $\widehat{\mathbf{x}_m}$ is a suitable Eora-classed $N \times 1$ proxy vector, in our case sectoral gross output, with the circumflex symbol (^) denoting diagonalization, and $\mathbf{1}$ is a $N \times 1$ vector for normalization weights. The map **M** can then be used to convert data according to $Eoradata = FAOdata \times \mathbf{M}$.

Integrating the Two Sets of Nitrogen Emissions Data

The calculus described in the three previous subsections results in a detailed data set on nitrogen emissions. However, it has two shortcomings. First, the FAO dataset does not cover emissions from industry and transport, for example. Second, FAO-based nitrogen emissions data (FAO-based N satellites) do not differentiate NH_3 (N_{NH3}) and NO_x (N_{NOx}). Therefore we used additional data from EDGAR (Kanemoto *et al*., 2014) to complete the sector coverage and to differentiate the Nr compounds. The data set of EDGAR-based emissions (EDGAR-based satellites) provide separate data for NH_3, NO_x, and N_2O, distributed by 55 detailed emission sources: five of them are the same as the FAO-based agricultural sources, in addition there exist 50 emission sources for industry, utility and transport losses. In order to integrate FAO and EDGAR, we first converted all data into units of nitrogen content, using stoichiometric mass ratios, and assuming all NO_x as NO_2 (compare the standard procedure in Leach *et al*., 2012). Then, because the most recent year for EDGAR data of NH_3 and NO_x is 2008, we forecasted EDGAR 2000-2008 data to 2010 by regression using generalized linear mixed models (GLMM) and Akaike's information criteria (AIC). We predicted quantities of each emission source in each country by appropriate explanatory valuables; we used EIA fuel consumption data (e.g. coal, gas, and petrol) for fuel-related emissions, FAO data (e.g. animal population and burnt area) for agricultural emissions and emissions of grassland fires, and UN population data for waste-related emissions. We employed log-transformed values for both response and explanatory variables, and included country as a random effect to consider unexplained variations among countries. We split EDGAR 2010 country data of NH_3, NO_x, and N_2O to Eora economy sectors to update EDGAR-based satellites (Kanemoto *et al.*, 2014). We also split FAO-based combined N satellites of NH_3 and NO_x into separate forms using the ratio of the EDGAR-based satellites of NH_3 and NO_x for agricultural sources.

Extended Input–Output Analysis

We applied the method of economic input–output analysis for enumerating the NF of the world's economies. Developed by Nobel Prize laureate Wassily Leontief in 1966 (Leontief, 1966), input–output analysis is a well-established technique for investigating the impacts of international trade. In particular, MRIO analysis is increasingly being used for undertaking consumption-based environmental accounting (Feng *et al.*, 2011; Lenzen *et al.*, 2012b; Wiedmann *et al.*, 2010). In the following, we explain the mathematical framework underlying MRIO analysis.

For undertaking MRIO analysis, a set of input–output matrices are required—an $N \times N$ intermediate transactions matrix $\mathbf{T}$ that contains monetary transactions data on the intermediate demand for goods and services within and between countries, an $N \times K$ final demand matrix $\mathbf{y}$, and a $M \times N$ value-added matrix $\mathbf{v}$, where N is the number of industry and products ('economic sectors') in all countries, K is the number of final demand categories, and M is the number of value-added categories. The data were taken from the Eora MRIO database (Lenzen *et al.*, 2013b, 2012a). This database covers 188 countries with 26 to 511 sectors each, and a total of almost 15,000 sectors. The input–output balance of the economy is written as $\mathbf{x} = \mathbf{T1} + \mathbf{y}$, where $\mathbf{x}$ is a N×1 vector called gross output. The $N \times 1$ vector $\mathbf{1}$ is a summation operator summing entries of $\mathbf{T}$ along one row. Then, the fundamental input–output equation can be written as $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{I}$ is an $N \times N$ identity matrix, $\mathbf{A}$ is an $N \times N$ direct requirements matrix defined as $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$, the circumflex symbol (^) denote diagonalization and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the so-called Leontief inverse that includes all the direct and indirect links between industries (see Appendix 1.1.1 for basic introduction of MRIO analysis). To analyse global flows of embodied nitrogen, we extended the fundamental input–output theory by adding data on five nitrogen satellite accounts —$\mathbf{Q}_{\mathbf{Nwp}}$, $\mathbf{Q}_{\mathbf{NH3}}$, $\mathbf{Q}_{\mathbf{NOx}}$, $\mathbf{Q}_{\mathbf{N2O}}$ and $\mathbf{Q}_{\mathbf{Ntotal}}$, where $\mathbf{Q}$ is a $1 \times N$ satellite accounts matrix and the subscript refers to the type of nitrogen indicator. The satellite accounts $\mathbf{Q}$ were constructed at a detail of 188 countries. To capture the most important component of Nr, namely food production, nitrogen emissions to water stemming from nitrogen fertilizers and livestock manures were compiled using FAO data and International Fertilizer Industry Association (IFA) data both for the year 2010, as well as NH_3, NO_x and N_2O emissions to air caused by nitrogen fertilizers and livestock manures.

We complemented this nitrogen satellite account with the Eora MRIO database with matching country detail for the year 2010 (Lenzen *et al.*, 2013b, 2012a). The direct nitrogen intensities were then calculated as $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$, where the vector **q** describes the amount of nitrogen emissions per unit of total output. In contrast, the multiplier **m**, where $\mathbf{m} = \mathbf{qL}$, includes both the direct and indirect flow-on impacts rippling through the complex supply chains. Nitrogen footprints **F** can then be calculated according to $\mathbf{F} = \mathbf{qLy}$.

Direct Emissions from Consumption

To calculate direct emissions from consumption (mainly household), we summed up emissions from sewage and EDGAR data split to consumption sectors. To estimate water emissions from sewage, we first calculated the amount of nitrogen supplied in food for each country using supplied protein data from FAO food balance sheets (FAOSTAT, 2015) multiplied by 0.16 (compare the standard procedure in Leach *et al.*, 2012). Next, we calculated the consumed nitrogen in food using FAO food waste data for ten regions (FAO, 2011). We then calculated discharged emissions from sewage using wastewater treatment data (Galloway *et al.*, 2014; OECD, 2013; UNEP and WHRC, 2007), assuming removal ratios of 35% for secondary treatment and 70% for tertially treatment (Stevens *et al.*, 2014; Wu, 1999) where detailed removal ratios were missing. Most of developing countries are assumed to discharge all consumed nitrogen in food to sewage. Data categories of countries/areas are explained in Table A.4.

2.3.2 Structural Path Analysis

In order to understand bilateral relationships and the commodity content of supply chains, we unravel footprints **F** using Structural Path Analysis (Crama *et al.*, 1984; Defourny and Thorbecke, 1984; Lenzen, 2002; Treloar, 1997). In essence, this technique allows the decomposition of the product **qLy** into components of the series expansion of the Leontief inverse $\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots$ (Waugh, 1950). Components of 1st order are $q_i y_i$, of 2nd order $q_i A_{ij} y_j$, 3rd order $q_i A_{ij} A_{jk} y_k$, and so on. The entire footprint can also summarily be decomposed using terms $q_i L_{ij} y_j$. These decomposition techniques were used to arrive at the results described under Figure 2.6 and Tables 2.3–2.5.

2.3.3 Production layer decomposition

As our study uses (top-down) MRIO analysis for enumerating the NF of nations, it allows a comprehensive appraisal of the entire supply chains in terms of the nitrogen emitted directly and indirectly for the sake of satisfying final (consumer) demand. For example, the emissions from animal manure were first allocated to livestock, and then allocated to meat production and to hides and skins in monetary order for the first, or higher, supply chain layer (or tier) through the MRIO analysis. Such supply-chain analyses are sometimes carried out using (bottom-up) process analysis (Bullard *et al*., 1978; Moskowitz and Rowe, 1985; Suh *et al*., 2004). Whilst input–output analysis is affected by errors resulting out of aggregation of detailed products into broad industry sectors (Section 2.3.4), process analyses are limited by a systems boundary that is drawn to delineate only those parts of the supply chain for which data can be collected manually. This delineation results in a so-called *truncation error*. Imagine a task of enumerating the NF of a product manufactured by an industry that has 100 suppliers. In the first instance the nitrogen emissions of that industry, plus its 100 suppliers need to be established, requiring the estimation of 100 values. If each of the 100 suppliers had 100 suppliers themselves, then the second supply chain tier would count 10,000 suppliers. The third and fourth supply-chain tiers would include 1,000,000 and 100,000,000 entities respectively. For a typical process analysis relying on manual data collection, it is clearly infeasible to amass such large-scale information – hence the system truncation. input–output analysis, on the other hand, covers an infinite number of supply-chain tiers, by means of the matrix inversion (Suh and Heijungs, 2007; Waugh, 1950). Using production layer decomposition in an input–output setting, one can calculate separately the contributions of each supply-chain tier to the complete footprint (Lenzen, 2008). This technique exploits the series expansion of the Leontief inverse $L = I + A + A^2 + A^3 + \ldots$(Waugh, 1950). Using the data described in method, we evaluated the global NF as a cumulative function of supply-chain tiers (Figure A.1). Assuming that the conventional N-calculator covered contributions up to the 2nd tier (N-Print, 2011), the system truncation would inadvertently lead to ignoring almost 55% of the nitrogen emissions. Even a system truncation beyond the third tier (requiring 1,000,000 data points to be collected manually) would still lead to a truncation error of almost 40%. Therefore, undoubtedly, bottom-up process analysis results in significant truncation errors. Similar truncation errors arise if instead of a MRIO framework, single-region input–output (SRIO) tables are used, since all international feedback loops would be ignored (Galloway *et al*., 2014; Lenzen *et al*., 2004) .

2.3.4 Aggregation errors in MRIO analysis

It is well known that input–output analysis is adversely affected by effects of sector aggregation (Lenzen, 2011; Steen-Olsen *et al.*, 2014; Su *et al.*, 2010; Zhou *et al.*, 2013). In a NF analysis, such effects can arise when nitrogen emissions per unit of output can vary significantly across crop and livestock types, and some of those crop and livestock types are aggregated into a broad industry sector. Ideally, such effects are avoided by utilizing input–output data with sufficiently high sector detail, so that crop and livestock types correspond to separate individual industry sectors in the input–output database.

In our work, most of the large and wealthy nations (such as the USA and Australia) but also some developing nations (such as India) are represented by a sufficiently disaggregated input–output database. However some developing economies in the Eora MRIO database are only described by 26 sectors, including one 'Agriculture' aggregate, combining all crops and livestock. For some of these countries, aggregation errors occurred in our work (Table 2.2).

If a nitrogen-intensive crop or livestock that is predominantly consumed domestically (for example cattle in Ethiopia) is aggregated within one broad industry sector (for example 'Agriculture') with a crop or livestock that incurs fewer nitrogen emissions but constitutes an important export (for example coffee in Ethiopia), an undue amount of nitrogen becomes allocated to the exported commodity, leading to erroneous footprint distributions across countries. This is due to the inherent inability of the MRIO database to distinguish between the aggregated commodities.

In this work we dealt with aggregation errors by manually adjusting structural paths $q_i L_{ij} y_j$ after the Leontief inversion, thus correcting for mis-allocation due to sector aggregation (Crawford, 2008; Lenzen and Crawford, 2009; Treloar, 1997). For example, amounts of nitrogen erroneously embodied in Ethiopian coffee exports to Japan were re-allocated to domestic Ethiopian farming (see list in Table 2.2).

Table 2.2 Countries and export commodities affected by aggregation errors.

Country of origin	Main exported goods
Antigua and Barbuda	Margarine, processed fruits and nuts, raw tobacco
Bahamas	Hard liquor
Bangladesh	Raw tobacco, ginger
Belarus	Raw sugar
Bermuda	Wheat, hard liquor, soybeans, corn
Brunei Darussalam	Dried legumes
Cape Verde	Foliage, oil seeds

Cayman Islands	Coffee, vegetable saps
Central African Republic	Raw cotton, Coffee
Chad	Raw cotton
Côte d'Ivoire	Cocoa beans
Egypt	Citrus fruits
Ethiopia	Coffee
Ghana	Cocoa beans
Guyana	Rice
Madagascar	Vanilla, clove
Mali	Raw cotton
Morocco	Tomatoes, citrus fruit
Myanmar	Dried legumes
Netherlands Antilles	Malt, onions
Nigeria	Cocoa beans
Samoa	Coconut oil
Seychelles	Palm oil
Tanzania	Raw tobacco, coffee, nuts
Uganda	Coffee
Zimbabwe	Raw tobacco

2.3.5 Uncertainty analysis of footprints

The uncertainty analysis was carried out using standard error propagation methods. In general, a footprint is calculated by using the formula

$$\mathbf{f} = \mathbf{qLy}, \qquad (1)$$

where $\mathbf{f}$ is the footprint vector, $\mathbf{q}$ is the matrix of nitrogen intensities, $\mathbf{L}$ is the Leontief-inverse, and $\mathbf{y}$ is the final demand vector.

For this section it is assumed that $\mathbf{q} \in \mathbb{R}^{1\times N}$ is a single row-vector. It is further assumed that $\mathbf{L} \in \mathbb{R}^{N\times N}$ with elements L_{ij}, $i, j = 1, \ldots, N$, and $\mathbf{y} \in \mathbb{R}^{N\times 1}$ with elements y_j, $j = 1, \ldots, N$. Additionally, the final demand vector $\mathbf{y}$ is assumed to be the final demand vector for a single country, yielding the corresponding NF for that particular country.

Assume that every numeric value contained in $\mathbf{q}$, $\mathbf{L}$, and $\mathbf{y}$ is the expected value of a random variable. The reliability of each of these values is then given by the standard deviation of that value. These standard deviations form the basis for the uncertainty analysis of the footprint results.

Equation 1 can be interpreted as a function as follows.

$$\mathbf{f} = f(q_{i_{i=1,\ldots,N}},\ L_{i,j\ {i,j=1,\ldots,N}},\ y_{j_{j=1,\ldots,N}}) = \mathbf{qLy}. \qquad (2)$$

According to the rules of error propagation, the standard deviation σ_f of the footprint **f** is then given by

$$\sigma_f = \sqrt{A + B + C}, \qquad (3)$$

where $A = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial q_i}\right)^2 \mathrm{var}(q_i)$, $B = \sum_{i=1}^{N} \sum_{j=1}^{N} \left(\frac{\partial f}{\partial L_{ij}}\right)^2 \mathrm{var}(L_{ij})$, $C = \sum_{j=1}^{N} \left(\frac{\partial f}{\partial y_j}\right)^2 \mathrm{var}(y_j)$.

Define the *relative standard deviation* of a given value $\boldsymbol{x}$ as

$$\frac{\sigma_x}{x}.$$

In this work we calculated the components A and C of Equation 3 explicitly, whilst for the calculation of term B we used an approach by Heijungs and Lenzen (2014). For the terms A and C we needed the variances of the individual elements of **q** and **y**. The Eora model supplies the standard deviations for each value of the intermediate transaction matrix **T**, the final demand block **Y**, and the value added block **V**. The country-wise final demand vectors **y** that were used to obtain the country-wise footprints are the sum over all six final demand categories in Eora (household final consumption; non-profit institutions serving households; government final consumption; gross fixed capital formation; changes in inventories; and acquisitions less disposals of valuables) for each country. Therefore, the standard deviations of the individual elements of the final demand block for each country must be considered for the calculation of the variances of the y_j. Let $\mathbf{Y}^c$ be the final demand block of the country identified by the superscript c, and let $\sigma_{Y_{jk}^c}$ be the standard deviation for the element Y_{jk}^c of $\mathbf{Y}^c$. Then $\mathbf{Y}^c \in \mathbb{R}^{N\times 6}$ and one element y_j of the country-wise final demand vector **y** was calculated as follows.

$$y_j = \sum_{k=1}^{6} Y_{jk}^c.$$

According to the laws of error propagation, the variance $\mathrm{var}(y_j) = \sigma_{y_j}^2$ for y_j is then given by

$$\mathrm{var}(y_j) = \sum_{k=1}^{6} \sigma_{Y_{jk}^c}^2. \qquad (4)$$

For the calculation of term A of Equation 3, it is necessary to estimate standard deviations for $\mathbf{q}$. Since $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$, where $\mathbf{Q}$ is the nitrogen satellite block and $\mathbf{x}$ is the total output of the Eora input–output system, it is sufficient to estimate standard deviations for $\mathbf{Q}$. The standard deviations for $\mathbf{x}$ can be obtained from the standard deviations supplied with the Eora model.

Lenzen *et al.* (2010) found that in general within a dataset, individual data points have a better reliability if the absolute value of the data point is larger. We further show that a power-regression model is the most appropriate modelling approach for the relative standard deviation values. This means that the relative standard deviations behave linearly with respect to the order of magnitude of the corresponding data points. Hence, for a data set with values *x*, the corresponding relative standard deviations can be estimated using the following linear function

$$\frac{\sigma_x}{x} = m \cdot \log_{10}(x) + b, \tag{5}$$

where m and b are the parameters of the linear function. In order to estimate relative standard deviations, values for the relative standard deviation were assigned to the largest and the smallest value of the dataset. The parameters m and b were then calculated from these two known function values, and the remainders of the relative standard deviations were then calculated using the linear equation.

Each value within the satellite block was calculated by multiplying data from the FAOSTAT data (FAOSTAT, 2015) and a multiplier provided by the IPCC (2006). IPCC data set provide information on the reliability of the data by giving ranges for the relative error in each data set. Following the methodology of Lenzen *et al*. (2010), we interpreted the upper boundary of each error range as the relative standard deviation of the smallest value within the dataset, and the lower boundary of the error range as the relative standard deviation of the largest value of the dataset. The error range of FAOSTAT data can be assumed as 1%-15% based on Smil (1999). The relative error range of the IPCC indicators can be assumed as the following: N_2O: 1%-68%; Nwp: 1%-56%; for NH_3 and NO_x: 1%-61%.

In the IPCC guidelines, the model to calculate the Nwp indicator takes into account soil water-holding capacity, rainfall, and irrigation of regions. However, we set the same coefficient for all regions as water emissions potential from the consumption perspective, i.e. consumers responsibilities are not dependent on the capacity of the producing region of the products that are consumed.

Using standard laws of error propagation for multiplication, we then calculated the relative standard deviation for the smallest and largest value in each indicator set from the error ranges provided by FAOSTAT and the IPCC, and then used Equation 5 to calculate the relative standard deviations for each indicator in the satellite block.

The set of standard deviations for Q completes the set of input data that are required to evaluate Equation 3. The remainder of this section will focus on the calculation of the different terms of the equation.

1. Calculation of $\frac{\partial f}{\partial q_i}$

Equation 2 can be rewritten as

$$\mathbf{f} = \sum_{i=1}^{N} q_i (\mathbf{Ly})_i,$$

where $(\mathbf{Ly})_i$ is the i-th element of the column vector **Ly**. We therefore obtained

$$\frac{\partial f}{\partial q_i} = (\mathbf{Ly})_i. \qquad (6)$$

2. Calculation of var(q_i)

In order to calculate the variance of **q**, we must first calculate the variance of the total output **x**. Let T_{ij} be an element of intermediate transaction matrix **T** and let $\sigma_{T_{ij}}$ be the corresponding standard deviation of that element. For the final demand block **Y** let Y_{ik} be the individual elements of **Y** and let $\sigma_{Y_{ik}}$ be the corresponding standard deviation. Note that for the calculation of the **x** we consider the total final demand block, and not the country-specific final demand block as we did further up. Assume that **Y** has the dimension $[N \times M]$. One element x_i of the total output **x** is calculated as follows.

$$x_i = \sum_{j=1}^{N} T_{ij} + \sum_{k=1}^{M} Y_{ik}.$$

According to the laws of error propagation, the standard deviation σ_{x_i} for x_i is then given by

$$\sigma_{x_i} = \sqrt{\sum_{j=1}^{N} \sigma_{T_{ij}}^2 + \sum_{k=1}^{M} \sigma_{Y_{ik}}^2}$$

Each element q_i of $\mathbf{q}$ is the result of a division of the two random variables Q_i and x_i. Using the laws of error propagation for the division of two random variables, we have

$$\frac{\mathrm{var}(q_i)}{q_i^2} = \left(\frac{\sigma_{Q_i}}{Q_i}\right)^2 + \left(\frac{\sigma_{x_i}}{x_i}\right)^2.$$

And therefore

$$\mathrm{var}(q_i) = q_i^2 \left[\left(\frac{\sigma_{Q_i}}{Q_i}\right)^2 + \left(\frac{\sigma_{x_i}}{x_i}\right)^2\right]. \quad (7)$$

3. Calculation of term B of Equation 3

According to Heijungs and Lenzen (2014), Eq. 47, this term can be calculated as follows.

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\left(\frac{\partial f}{\partial L_{ij}}\right)^2 \mathrm{var}(L_{ij}) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[(\mathbf{qL})_i(\mathbf{Ly})_i \ln(10)\, A_{ij}\right]^2 \mathrm{var}\left(\log_{10}(T_{ij})\right)$$

$A_{i,j}$ are the elements of the matrix $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$.

Using the standard laws of error propagation we can rewrite the term var $(\log_{10}(T_{ij}))$ as follows.

$$\mathrm{var}\left(\log_{10}(T_{ij})\right) = \left[\frac{d}{dT_{ij}}\left(\log_{10}(T_{ij})\right)\right]^2 \mathrm{var}(T_{ij})$$

Using

$$\frac{d}{dT_{ij}}\left(\log_{10}(T_{ij})\right) = \frac{d}{dT_{ij}}\left(\frac{\ln(T_{ij})}{\ln(10)}\right) = \frac{d}{dT_{ij}}\left(\ln(T_{ij})\frac{1}{\ln(10)}\right) = \frac{1}{T_{ij}\ln(10)},$$

we obtain

$$\operatorname{var}\left(\log_{10}(T_{ij})\right) = \left[\frac{1}{T_{ij}\ln(10)}\right]^2 \operatorname{var}\left(T_{ij}\right).$$

Hence

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\left(\frac{\partial f}{\partial L_{ij}}\right)^2 \operatorname{var}\left(L_{ij}\right)$$
$$= \sum_{i=1}^{N}\sum_{j=1}^{N}\left[(\mathbf{qL})_i(\mathbf{Ly})_i \ln(10)\, A_{ij}\right]^2 \left[\frac{1}{T_{ij}\ln(10)}\right]^2 \operatorname{var}\left(T_{ij}\right)$$
$$= \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\frac{(\mathbf{qL})_i(\mathbf{Ly})_i A_{ij}}{T_{ij}}\right]^2 \operatorname{var}\left(T_{ij}\right). \qquad (8)$$

4. Calculation of $\frac{\partial f}{\partial y_i}$

This calculation follows closely the calculation of $\frac{\partial f}{\partial q_i}$ and the result is given by

$$\frac{\partial f}{\partial y_i} = (\mathrm{qL})_i. \qquad (9)$$

5. Calculation of var(y_i)

As written earlier in this section, the variance var(y_j) is given Equation 4 as

$$\operatorname{var}(y_j) = \sum_{k=1}^{6}\sigma^2_{Y^c_{jk}}.$$

Figure 2.2 shows the relative uncertainty of each footprint vs the order of magnitude of the corresponding footprint value for the individual indicators. The plot shows that larger relative standard deviations are of a small or medium order of magnitude. This shows that in general the footprint values show a high reliability, with low reliability only occurring for some small or medium footprint values.

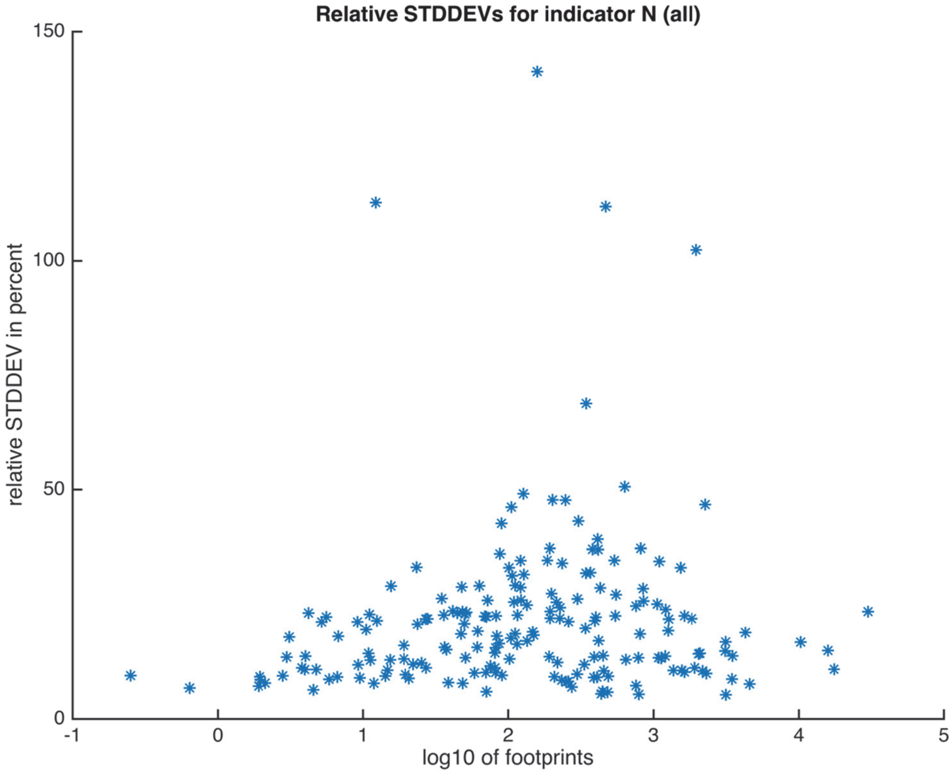

Figure 2.2 Relative standard diviations for nitrogen footprints of nations.

2.3.6 Data Availability

The data used and results are available online as follows.

- Production data (FAOSTAT): faostat3.fao.org/home
- Fertilizer data (IFA): http://www.fertilizer.org/imis20/images/Library_Downloads/AgCom.13.39%20-%20FUBC%20assessment%202010.pdf
- Air emissions data from industries (EDGAR): http://edgar.jrc.ec.europa.eu/datasets_list.php?v=42
- Multi-region input–output (MRIO) database: http://worldmrio.com
- Wastewater treatment data (OECD): http://dx.doi.org/10.1787/9789264185715-en
- Nitrogen emissions satellites: http://worldmrio.com

2.4 Results and Discussion

Of the 189 Tg (= 10^{12} g) of Nr emitted worldwide in 2010, 161 Tg were emitted from industries and agriculture (75 Tg organic and inorganic nitrogen (mainly NO_3^-) in leaching and runoff, emitted to surface and underground water (for the sake of brevity we will we refer to this as the nitrogen potentially exportable to water [Nwp]); 45 Tg of NH_3 and 6.2 Tg of N_2O (mainly from agriculture); and 35 Tg of NO_x (mainly from transport and energy generation)) and 28 Tg were emitted by consumers (including 27 Tg of Nwp mainly from sewage). The world-average per-capita NFs are 27 kg yr^{-1}, ranging from more than 100 kg cap^{-1} yr^{-1} for wealthy nations such as Hong Kong and Luxembourg, to less than 7 kg cap^{-1} yr^{-1} for developing nations such as Papua New Guinea, Côte d'Ivoire and Liberia. These differences reflect wealthy consumers' preference for animal products and highly processed food, as well as their dependence on energy-intensive goods and services (see a complete list of countries in Figure 2.3). Our results of per-capita NFs are higher than those presented in previous studies (Leach *et al*., 2012; Pierer *et al*., 2014; Shibata *et al*., 2014; Stevens *et al*., 2014)—for example 62 kg cap^{-1} yr^{-1} for the USA compared to 41 kg cap^{-1} yr^{-1} (Leach *et al*., 2012)—because we include all upstream supply chains, whereas the previous studies focused on communication to individual consumers by taking a bottom-up approach (see Methods, Figure A.1 and Table A.5).

We find that four populous nations bear 47% of the global Nr emissions (China 20%, India 11%, the USA 10% and Brazil 6.1%), followed by another six nations (Russia, Pakistan, Indonesia, Australia, Mexico and Argentina) bearing an additional 12%. We also find that 41.8 Tg (or 26% of the total industrial and agricultural emissions) become embodied in international trade. This holds separately for Nwp (25% traded), and emissions of NH_3 (26%), NO_x (28%) and N_2O (27%). These percentages compare with international trade embodiments of threatened species (30%; Lenzen *et al*., 2012b), CO_2 (30%; Peters *et al*., 2012), scarce water (24%; Lenzen *et al*., 2013a) and employment (30%; Alsamawi *et al*., 2014).

Trade balances of embodied Nr vary significantly across nations (Figures 2.4 and 2.5). Net importing nations cause emissions abroad for their own consumption more than bearing domestic emissions for exports. For net exporters the opposite applies. On country basis, whereas the main net exporters are (often developing) countries with significant agricultural, food and textile export capacity, important net importers are almost exclusively developed economies. These developing-developed-country relationships in terms of NO_x and N_2O are in line with those found by Kanemoto *et al*. (2014),

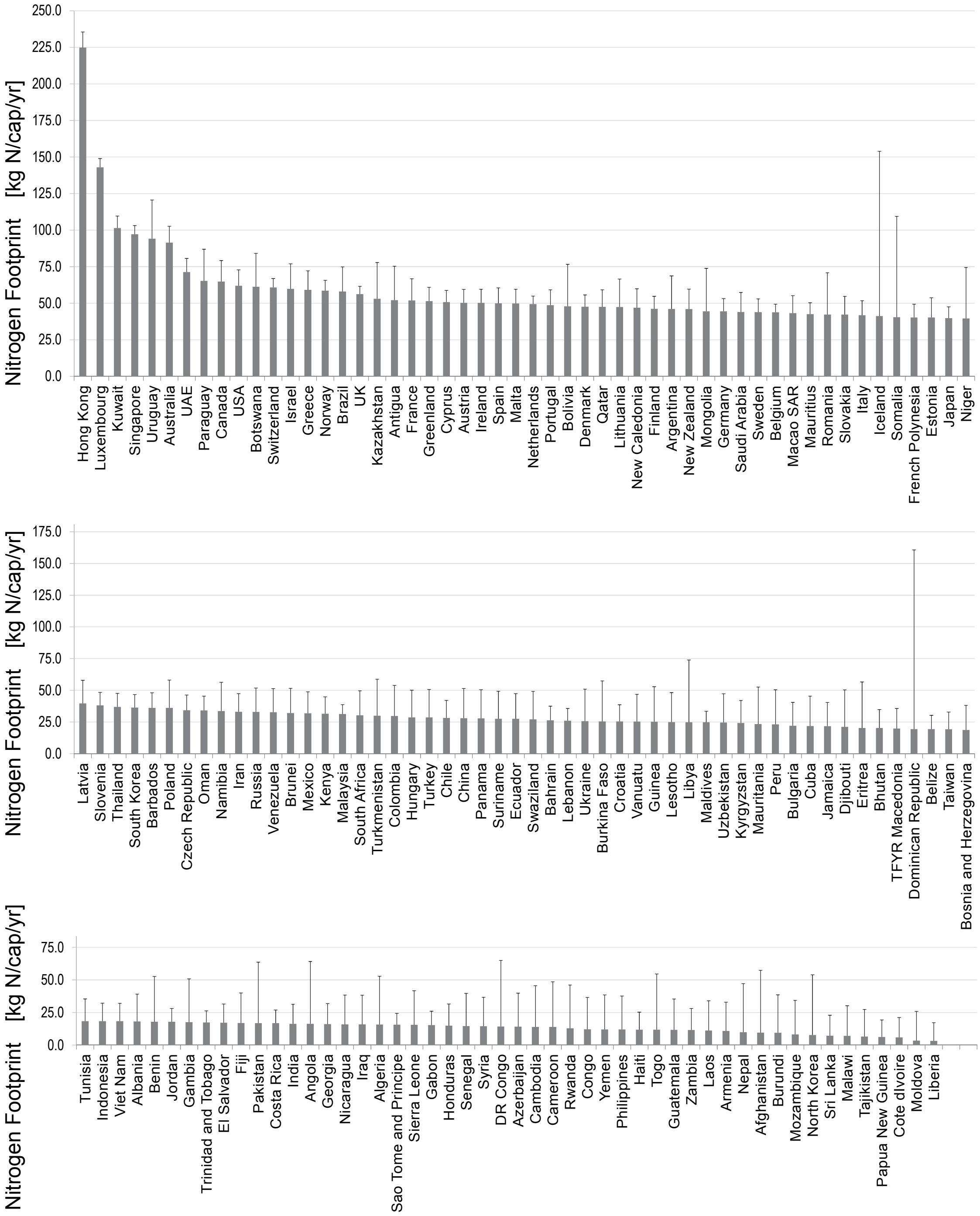

Figure 2.3 Ranked per-capita nitrogen footprints of nations. Values include both emissions induced domestically and abroad from industries and households for the nation's consumption. The error bars display the standard deviation of the corresponding footprint value (Section 2.3.5). Countries affected by aggregation errors (Table 2.2) and countries with data limitation (Andorra, Aruba, Liechtenstein, Monaco, Montenegro, Serbia, South Sudan, and Sudan; see details in Table A.4) are excluded.

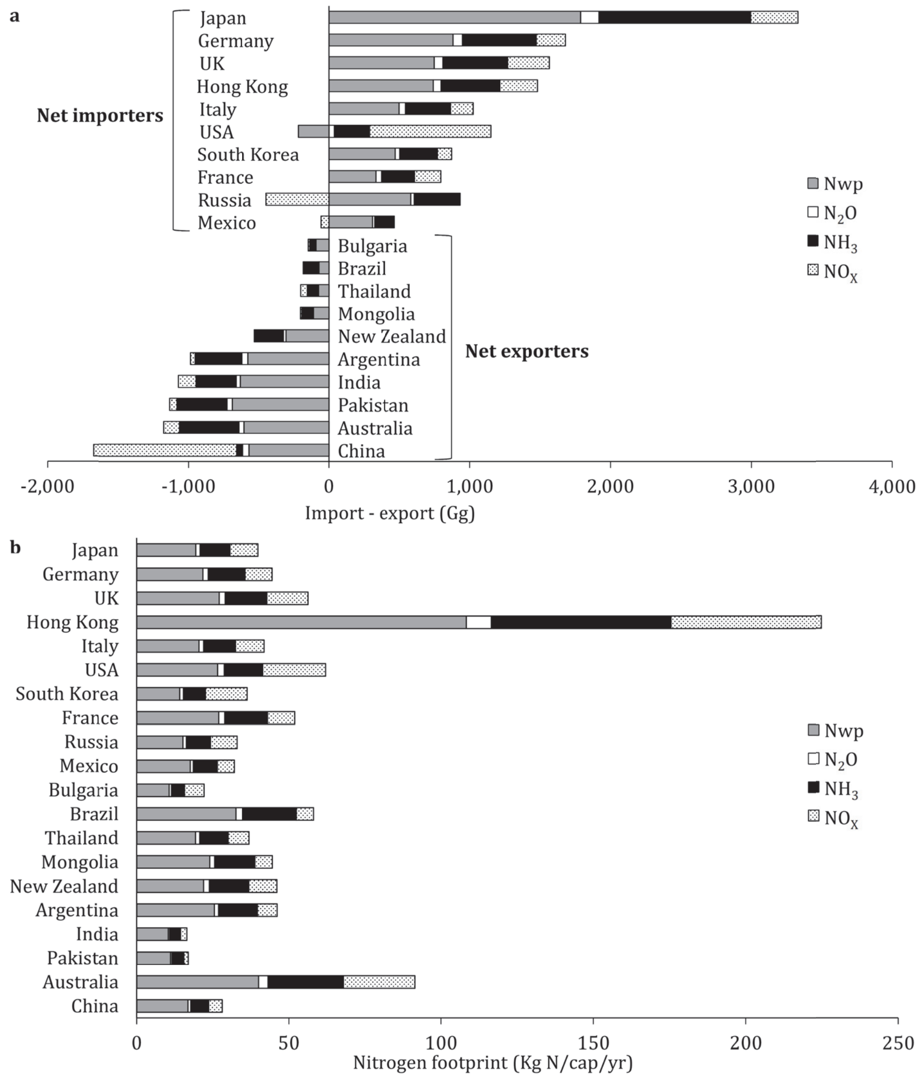

Figure 2.4 Embodied reactive nitrogen emissions and per-capita nitrogen footprints for top-10 net exporters and importers. a, Reactive nitrogen emissions. **b,** Per-capita nitrogen footprints. Net importers are causing emissions more abroad for the sake of satisfying their consumption than they generate emissions because of their exports, and vice versa for net exporters. Nwp: nitrogen potentially exportable to water bodies, mostly NO_3^-. Per-capita values include both emissions induced domestically and abroad from industries (including agriculture) and households for the nation's consumption.

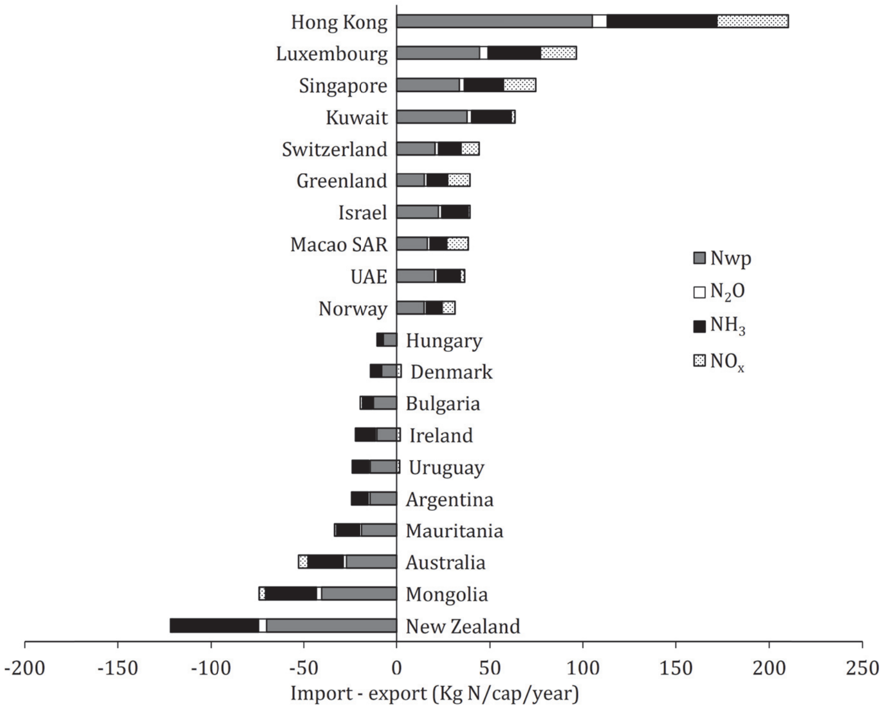

Figure 2.5 Per-capita top-10 net importers and exporters. Net importers are causing reactive nitrogen emissions more abroad for their consumption than emissions generated due to exports, and net exporters are bearing emissions for exports more than emissions caused abroad for their consumption. Nwp: nitrogen emissions potentials to water, mostly NO_3^-.

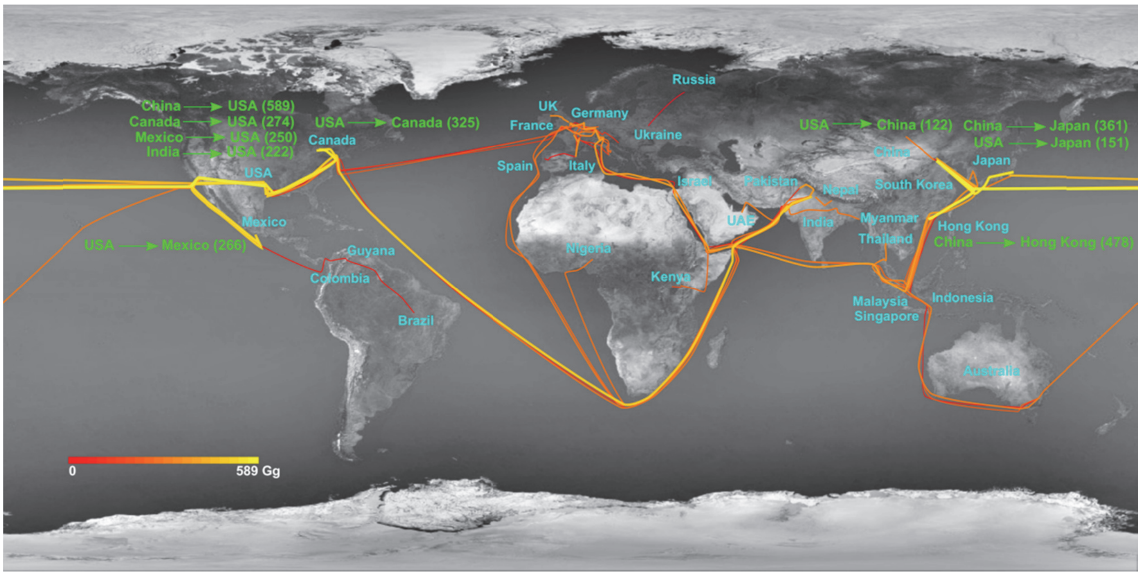

Figure 2.6 International flows of embodied reactive nitrogen emissions between countries of last sale and countries of consumption (top ten flows labelled). The colour of the arrows represents the amount of reactive nitrogen emissions embodied in the products traded between the linked countries. Supply-chain links with primary-producing and intermediate-processing countries are included in all flows.

but our study demonstrates similar relationships for much larger emissions of Nwp and NH_3. In Russia, emissions of NO_x from flaring in the petroleum and gas extraction industry become embodied in large petroleum product exports (Ismail and Umukoro, 2012). Similarly, China's NO_x embodied exports are large compared to those of other Nr species, because of emissions from coal-fired power plants providing the electricity for the production of China's manufactured exports. China's net Nwp and NH_3 exports are due to exports of vegetables, fruit and clothes, only partly offset by imports of soybeans and other crops.

On a per capita basis, while main net exporters are non-populated countries (not always developed countries) with significant livestock industry with large areas, main net importers are populated countries with high per-capita GDP and small agricultural areas (Figure 2.5). Main traded Nr species are Nwp and NH_3, indicating agricultural products as key players traded between net exporters and net importers. Most of the net importers also import NO_x embodied products, mainly from China (Figures 2.4 and 2.5).

Tracing the flows of embodied emissions across supply chains, we find that significant embodied Nr flows from China, India and Mexico to the USA and Japan (Figure 2.6). The USA is both an importer and exporter to China, Mexico and Canada, and many trade routes end with top importers such as Japan, Germany, the UK and Hong Kong. To understand the commodity traded on these routes of embodied Nr, we used structural path analysis (SPA, Section 2.3.2) to unravel the NF into top-ranking bilateral trade relationships (Tables 2.3–2.5). Japan and other developed nations import Nr embodied in Chinese made clothing as well as US-American and Australian meat (Table 2.3). Germany, the UK, Italy and France exchange significant amounts of Nr emissions embodied in food products. Hong Kong records its main Nr imports as primary agricultural and raw food products because it lacks land to produce its own livestock and crops. Developing countries such as China, India, Pakistan and Thailand embody large amounts of Nr emissions into their exports of textiles and clothing (Table 2.4). As high-income exceptions, Australia, New Zealand and Argentina export significant Nr embodied in livestock products.

As exemplified in previous work for example on carbon emissions (Barrett *et al.*, 2013; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008), footprint measures encompass notions of consumer responsibility for environmental pressure exerted by producers (Liu *et al.*, 2015). A notable example for a relationship between a hotspot of nitrogen pollution and a distant consumption centre is Tulare County, a major dairy- and cattle-producing region in the USA (Tulare County Agriculture Commissioner, 2015). 15%

of residents in the region, frequently of low-income Latino origin, are reported as being exposed to drinking water with concentrations of fertilizer- and manure-derived nitrates of more than half the maximum contaminant level (Balazs *et al.*, 2011). Many of those residents are at risk of adverse health outcomes and/or experience additional economic costs because of having to purchase bottled water. Nitrate contaminated water can cause "blue baby syndrome, a potentially fatal blood disorder that cuts off an infant's oxygen supply" (Lockhart *et al.*, 2013). Japan is one of the most important recipients of California's agricultural exports, many of which come from Tulare County (California Department of Food and Agriculture, 2012), and indeed Japan's supermarket shelves stack meat predominantly from Australia (58% of all beef meat imports) and the USA (37%). Our SPA reveals that bilaterally, 26 Gg of Nr are embodied in Japan's imports of meat from the USA, and that this supply chain alone represents 17% of Japan's embodied Nr imports from the USA. Of those, 15.3 Gg Nwp are released into the groundwater, as well as 9.0 Gg NH_3, 0.82 Gg N_2O and 0.99 Gg NO_X emitted to air, during the farming of cattle and growing of grains for fodder. Applying the carbon footprint's logic to global nitrogen flows means that Japanese consumers of US beef bear responsibility for the consequences of nitrogen contamination in the USA.

With the following assumptions, our results suggest that 9.2 Gg N year^{-1} emissions can be reduced in the USA together with another 1.8 Gg N year^{-1} emissions in other countries by encouraging young Japanese people to eat less meat and more vegetables for the good of their health and the environment (based on Shibata *et al.*, 2014). This result is calculated for achieving a $1 billion reduction per year in the Japanese final demand for the meat-related production sectors (slaughtering and meat processing, processed meat products, and bottled or canned meat products). This is accompanied by a $1 billion increase per year in the Japanese final demand for the USA' 'vegetable and melon farming' sector. The result is calculated assuming that the increase/reduction in input is proportional to the increase/reduction in output and ignores price changes, technological changes, and the prices of meat and vegetables.

A story including even larger traded Nr volumes unravels when following the path of clothing imported into Japan. Many of Japan's clothing giants stack merchandise from Guangdong province in China (Wang and Yue, 2010), where more than a quarter of Chinese-made clothes, leather and furs are produced (Golley, 2012). Guangdong's fibre, textile and dyeing sectors emit more wastewater than any other sector in Guangdong Province (Sustainable Development Strategy Study Group of Chinese Academy of Sciences, 2009) and thus contribute significantly to China's nitrogen and Chemical Oxygen Demand

Table 2.3 Main trading partners of embodied reactive nitrogen emissions for top ten net importers. The table shows the countries, their main sectors and the nitrogen embodied commodities that are traded between the countries.

Country	Main trading partners and their transactions of final sales (import origin, % of total embodied nitrogen emissions embodied in the transaction, main exporting sector of the trading partner, main imported commodity)	Embodied nitrogen emissions of net import (Gg)
Japan	- China, 33, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts. - USA, 14, *Animal (except) poultry, slaughtering, rendering and processing*, bovine meat, swine meat. - Australia, 7, *Fresh meat*, bovine meat, edible offal of animals, lamb meat. - India, 4, *Hotels and restaurants*, Soybean oilcake, extracts, juices of meat and fish, fruit, nuts and edible plants preserved with sugar. - Thailand, 4, *Restaurant and drinking place*, homogenised preparations of meat, prepared or preserved fish, pasta, sauces and seasonings, sausages.	1227
Germany	- China, 8, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts. - Netherlands, 7, *Food products and beverages*, fruit juices, soybean oilcake, beer, waters flavoured or sweetened sauces and seasonings, cocoa butter, fat, oil. - India, 6, *Leather and leather products*, leather footwear, articles of apparel of leather, other articles of leather, saddlery and harness for any animal, tanned hides and skins of bovine or equine animals. - France, 5, *Food products and beverages*, wine of fresh grapes, homogenised vegetable preparations, sausages, malt extract, bread, pastry, cakes, biscuits and other baked goods, cocoa powder (sweetened). - USA, 5, *Tree nut farming,* Tree nuts.	1372
UK	- Netherlands, 10, *Food products and beverages*, sauces and seasonings, other vegetables, prepared or preserved, fruit juices, ice cream, water flavoured or sweetened, cocoa powder (sweetened), soybean cake, beer, bread, pastry, cakes, biscuits and other baked goods. - China, 8, *Leather, furs, down and related products*, trunks or cases, articles of apparel of leather, saddlery and harness for any animal, leather footwear. - Germany, 8, *Food products*, bread, pastry, cakes, biscuits and other baked goods, homogenised preparations of meat, cigars, fruit juices, beer, wine of fresh grape, cocoa powder (sweetened). - Ireland, 8, *Food products and beverages*, homogenised preparations of meat, malt extract, beer, bread, pastry, cakes, biscuits and other baked goods, water flavoured or sweetened, fermented beverages (cider, perry, mead, etc.). - France, 7, *Food products and beverages*, wine of fresh grapes, alcohol preps for beverages, beer, bread, pastry, cakes, biscuits and other baked goods, ice cream, beer.	1030

Hong Kong	- **China, 43, *Crop cultivation*, dried vegetables, lettuce, apples, wheat or meslin flour plants used in perfumery, in pharmacy or for insecticide, rice and tea.** - **USA, 8, *Animal production*, *except cattle and poultry and eggs*, swine meat and lamb meat.** - **Kenya, 7, *Other livestock*, fish flours, meals and pellets for human consumption, fish fillet or meat, guts of animals except fish, guts of animals except fish, molluscs.** - **Thailand, 6, Rice *milling*, rice.** - **Australia, 5, *Fresh meat*, bovine meat, lamb meat, edible offal of animals.**	**1111**
Italy	- Germany, 12, *Food products*, cigars, beer, bread, pastry, cakes, biscuits and other baked goods, malt extract, cocoa powder (sweetened). - France, 8, *Food products and beverages*, wine of fresh grapes, cereal foods, malt extract, bread, pastry, cakes, biscuits and other baked products, alcoholic preps for beverages, other vegetables (prepared or preserved), pasta. - Spain, 7, *Products of agriculture*, virgin olive oil, prepared or preserved fish, sauces and seasonings, fruit juices, homogenised vegetable preparations. - Netherlands, 7, *Food products and beverages*, cigars, beer, cocoa butter, fat, oil, malt extract, fruit juices, alcoholic preps for beverages. - China, 6, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts.	597
USA	- China, 23, *Leather, furs, down and related products*, leather footwear, trunks or cases, articles of apparel of leather, saddlery or harness for any animal, other articles of leather. - Canada, 11, *Agriculture, hunting, forestry and fishing*, canola, rape or mustard oil, wheat and meslin, tomatoes, dried legumes, potatoes, cucumbers, oats, soya beans, maize (corn) seed, barley, rice, fish fillet and meat. - Mexico, 10, *Agriculture*, tomatoes, cucumbers, frozen vegetables, onions and shallots, coffee, lettuce, dates, figs, pineapples, avocadoes, guavas mangoes, grapes, melons and citrus fruit. - India, 9, *Readymade garments*, women's and men's suits, t-shirts, sweaters, pullovers, sweatshirts, and babies' clothing. - Australia, 3, *Fresh meat*, bovine meat, lamb meat and edible offal of animals.	2587
South Korea	- China, 26, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts. - USA, 15 *Animal (except poultry) slaughtering, rendering, and processing*, bovine meat, swine meat, edible offal of animals. - Australia, 9, *Fresh meat*, bovine meat, lamb meat, edible offal of animals. - Japan, 6, *General eating and drinking places (except coffee shops)*, cigars, sauces and seasonings, fermented beverages (cider, perry, mead, etc.), beer, soups and broths. - India, 4, *Hotels and restaurants*, extracts of coffee, tea or mate, molasses, extracts, juices of meat or fish, jams and jellies, bread, pastry, cakes, biscuits and other baked goods.	343

France	- Spain, 9, *Products of agriculture*, sauces and seasonings, raw sugarcane, cocoa powder, soybean oilcake, extracts of coffee, tea or mate. - Germany, 8, *Food products*, bread, pastry, cakes, biscuits and other baked products, cocoa powder (sweetened), fruit juices, sauces and seasonings, homogenised preparations of meat, cigars, beer, water flavoured or sweetened. - Belgium, 6, *Food products and beverages*, beer, ice cream, confectionery sugar, sauces and seasonings, bread, pastry, cakes, biscuits and other baked products, cocoa powder (sweetened). - Netherlands, 6, *Food products and beverages*, fruit juices, beer, water flavoured or sweetened, cocoa powder (sweetened), malt extract, fruits, nuts and edible plants preserved with sugar. - India, 6, *Readymade garments*, women's and men's suits, t-shirts, sweaters, pullovers, sweatshirts, babies' garments, active wear.	1022
Russia	- Ukraine, 9, *Agriculture*, tomatoes, soya bean, cucumbers, apples, maize (corn) seeds, frozen vegetables. - Tajikistan, 8, *Agriculture*, Cotton, onions and shallots, apricots. - China, 6, *Other textiles not elsewhere classified*, house linen, woven fabrics of synthetic filament yarn, staple fibres. - Uzbekistan, 6, *Crops*, cotton, live plants with roots, plants used in perfumery, in pharmacy or for insecticide. - Germany, 5, *Food products*, extracts of coffee, tea or mate, wine of fresh grapes, beer, cocoa powder (sweetened), malt extract, fruit juices.	575
Mexico	- USA, 66, *Soybean and other oilseed processing*, soya beans, maize (corn) seed, wheat and meslin. - China, 4, *Crop cultivation*, seeds, fruits and spores for sowing, dried legumes, dried apricots, dried and frozen fruits and vegetables. - Chile, 3 *Meat*, lamb meat, poultry, horse. - Australia, 3, *Meat products*, lamb meat, bovine meat, swine meat, edible offal of animals. - Spain, 2, *Vegetable and animal oil and fat*, virgin olive oil, olive oil blends, hydrogenated animal and vegetable fats and oils, vegetable saps and extracts.	403

Table 2.4 Main trading partners of embodied reactive nitrogen emissions for top ten net exporters. The table shows the countries, their main sectors and the nitrogen embodied commodities that are traded between the countries.

Country	Main trading partners and their transactions of final sales (export destination, % of total embodied nitrogen emissions embodied in the transaction, main exporting sector of the trading partner , main exported commodity)	Embodied nitrogen emissions of net export (Gg)
China	- USA, 24, *Leather, furs, down and related products*, leather footwear, trunks or cases, articles of apparel of leather, saddlery and harness for any animal, other articles of leather, chamois leather. - Hong Kong, 19, *Crop cultivation*, dried vegetables, lettuce, apples, wheat or meslin flour plants used in perfumery, in pharmacy or for insecticide, rice and tea. - Japan, 15, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts. - Germany, 5, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts. - South Korea, 4, *Wearing apparel*, sweaters, pullovers, sweatshirts, women's suits, men's suits, t-shirts.	2504
Australia	- Japan, 13, *Fresh meat*, bovine meat, edible offal of animals, lamb meat. - USA, 12, *Fresh meat*, bovine meat, lamb meat, edible offal of animals, guts of animals. - Hong Kong, 10, *Fresh meat*, bovine meat, lamb meat, edible offal of animals. - China, 9, *Fresh meat*, lamb meat, bovine meat, guts of animals, edible offal of animals. - Singapore, 7, *Fresh meat*, swine meat, bovine meat, lamb meat, other meat and edible meat offal.	608
Pakistan	- India, 24, *Agriculture*, Cotton and wool. - USA, 14, *Textiles and wearing apparel*, house linen, men's shirts, t-shirts, men's suits, women's suits, sweaters, pullovers and sweatshirts. - Germany, 8, *Textiles and wearing apparel*, house linen, men's shirts, t-shirts, men's suits, carpets, gloves, mittens and mitts. - China, 8, *Agriculture*, dried apricots, dried legumes, dried vegetables, potatoes, vegetable products, vegetable saps and extracts. - Saudi Arabia, 6, *Agriculture*, rice, citrus fruit and ginger.	452
India	- USA, 20, *Readymade garments*, women's and men's suits, t-shirts, sweaters, pullovers, sweatshirts, babies' garments, active wear. - Germany, 8, *Leather and leather products*, leather footwear, articles of apparel of leather, other articles of leather, saddlery and harness for any animal, tanned hides and skins of bovine or equine animals. - UAE, 7, *Miscellaneous food products*, confectionery sugar, bread, pastry, cakes, biscuits and other baked goods, extracts of coffee, tea or mate, fruits, nuts and edible plants preserved with sugar. - UK, 6, *Readymade garments*, women's and men's suits, t-shirts, sweaters, pullovers, sweatshirts, babies' garments, active wear. - France, 5, *Readymade garments*, women's and men's suits, t-shirts, sweaters, pullovers, sweatshirts, babies' garments, active wear.	1124

Argentina	- Brazil, 15, *Dairy products*, milk, cream, fresh cheese, whey and butter. - Germany, 11, *Meat and meat products*, bovine meat, poultry, lamb meat, horse, ass, mule or hinny meat, guts of animals and edible meat offal. - Italy, 8, *Meat and meat products*, bovine meat, horse, ass, mule or hinny meat, lamb meat, poultry and edible meat offal. - France, 6, *Meat and meat products*, molluscs, horse, ass, mule or hinny meat, bovine meat, edible meat offal and guts of animals. - Chile, 6, *Oils and animal fats and vegetables*, processed animal and vegetable oils, crude sunflower seed or safflower oil, hydrogenated animal and vegetable fats and oils, canola, rape and mustard oil.	371
New Zealand	- Germany, 10, *Meat and meat products*, lamb meat, bovine meat, guts of animals and edible meat offal, - UK, 9, *Meat and meat products*, lamb meat, bovine meat, molluscs and edible meat offal. - USA, 9, *Meat and meat products*, bovine meat, lamb meat, molluscs and edible meat offal. - China, 8, *Meat and meat products*, lamb meat, molluscs, guts of animals and bovines. - Australia, 8, *Other livestock*, Horses.	255
Mongolia	- China, 72, *Agriculture*, nuts, plants used in perfumery, in pharmacy or for insecticide, rape or colza seeds and dried vegetables. - Russia, 10, *Food and beverages*, horse, ass, mule or hinny meat, bovine meat, homogenised preparations of meat and lac. - USA, 7, *Textiles and wearing apparel*, men's undergarments, men's shirts, men's suits, sweaters, pullovers and sweatshirts. - Kuwait, 4, *Agriculture*, Tarpaulins, awnings and sunblinds. - Italy, 2, *Agriculture*, guts of animals, except fish.	107
Thailand	- Hong Kong, 19, *Rice milling*, rice. - USA, 14, *Wearing apparels except footwear,* babies' garments, men and women's undergarments, men's and women's suits and t-shirts. - Japan, 11, *Restaurant and drinking place*, homogenised preparations of meat, prepared or preserved fish, fruits, nuts and edible plants preserved with sugar, homogenised vegetable preparations, malt extract, sauces, seasonings and fruit juices. - China, 6, *Noodles and similar products*, instant noodles and pasta. - Indonesia, 4, *Noodles and similar product*, instant noodles and pasta.	353
Brazil	- USA, 14, *Footwear*, leather footwear, Footwear made of textiles. - Argentina, 9, *Other food products*, cocoa powder, Cocoa butter, Extracts of coffee and tea. - Germany, 9, *Oil, cakes, rind, flour, and other soy products*, soybeans, soybean oilcake, wheat and meslin. - Japan, 6, *Hotels and restaurants*, Poultry, guts of animals, soya beans. - France, 5, *Oil, cakes, rind, flour, and other soy products,* soybeans, soybean oilcake.	445
Bulgaria	- Germany, 17, *Agriculture*, sunflower seeds, rape or colza seeds, cucumbers, fruits and nuts (frozen), other vegetables, apricots (dried). - Greece, 15, *Agriculture*, wheat and meslin, maize (corn) seed, barley, sunflower seed or safflower oil and frozen vegetables. - Turkey, 10, *Agriculture*, sunflower seeds, rape or colza seeds, rice, worked cereal groats. - France, 8, *Food and beverages*, homogenised preparations of meat, bread, pastry, cakes, biscuits and other baked goods, cigarettes, prepared or preserved fish, waters flavoured or sweetened and alcoholic preps for beverages. - Italy, 6, *Agriculture*, wheat and meslin, maize (corn) seed, barley, fruits and nuts frozen, dried and frozen vegetables, and sunflower seeds.	62

Table 2.5 Representative sectoral trade paths among nations.

Emitter	Final Producer	Final Consumer
Mali's agriculture sector	Thailand's wearing apparel except footwear sector	USA
China's crop cultivation sector	China's wearing apparel sector	Japan
China's crop cultivation sector	China's wearing apparel sector	Germany
Netherlands's Agriculture, hunting and related service activities sector	Netherlands's Food products and beverages sector	United Kingdom
China's crop cultivation sector	China's crop cultivation sector	Hong Kong
Germany's agriculture and hunting sector	Germany's food products sector	Italy
China's livestock and livestock products sector	China's Leather, furs, down and related products sector	USA
China's crop cultivation sector	China's wearing apparel sector	South Korea
Spain's products of agriculture sector	Spain's products of agriculture sector	France
Ukraine's agriculture sector	Ukraine's agriculture sector	Russia
USA's oilseed farming sector	USA's soybean and other oilseed processing sector	Mexico
Australia's beef cattle sector	Australia's fresh meat sector	Japan
Pakistan's agriculture sector	Pakistan's agriculture sector	India
India's other livestock products sector	India's readymade garments sector	USA
Argentina's live animals sector	Argentina's dairy products sector	Brazil
New Zealand's cattle sector	New Zealand's meat and meat products sector	Germany
Mongolia's agriculture sector	Mongolia's agriculture sector	China
Thailand's paddy sector	Thailand's rice milling sector	Hong Kong
Brazil's beef and other live animals	Brazil's footwear sector	USA
Bulgaria's agriculture sector	Bulgaria's agriculture sector	Germany

(COD) pollution (Gu *et al*., 2013a), and ultimately to health problems such as preterm births (Liu *et al*., 2013; Sun *et al*., 2015). More upstream, Nwp emissions come from cotton farming mainly in Xinjiang (Chen *et al*., 2010), and wool production in Jiangsu (Brown *et al*., 2005). Our SPA reveals that 115 Gg Nr emissions are embodied in Japan's imports of clothing from China, and this supply chain alone represents 32% of Japan's embodied Nr imports from China. Of those, 58 Gg N of Nwp are released into the groundwater, as well as 24 Gg N of NO_X, 5 Gg N of N_2O and 28 Gg N of NH_3 emitted to air, during cultivation of cotton (for fibres) and raising of livestock (for wool and leather). Once again, applying the carbon footprint's logic to global nitrogen fluxes means that Japanese consumers of Chinese clothing bear responsibility for the consequences of nitrogen contamination in China.

International policies to address nitrogen pollution are still in development, despite the significant role of international trade. Existing policies have been mainly limited by fragmentation separating Nr forms, media and sectors (SRU, 2015; Sutton *et al*., 2013), thus hindering the identification of trade-offs between the benefits of nitrogen as a critical nutrient for food production and the threats of nitrogen pollution. In the European Union (EU) and the USA, NO_x and NH_3 are covered in the Geneva (1979) and the Sofia (1998) protocols of the Conventions on Long-range Transboundary Air Pollution, the 1977 US Clean Air Act and the related EU Directives (the Emission Ceilings Directive and the Industrial Emissions Directive; see a summary of the EU directives in Chapter Four of the European Nitrogen Assessment)(AirClim, 2015), resulting in a considerable reduction of NO_x from point sources such as transportation and energy sectors. Likewise, NO_3^- from point sources (for example, sewage) has been reduced, guided by the 1992 Convention on the Protection of the Marine Environment of the Baltic Sea Area, the 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic, the 1977 US Clean Water Act, the Nitrates Directive, and the Water Framework Directive. Whereas mitigating point sources of NO_x, N_2O and NH_3 emissions can be achieved by end-of-pipe solutions such as catalytic reduction at plant and vehicle exhausts (EEA, 2014; Erisman *et al*., 2003), non-point sources of NO_3^-, NH_3 and N_2O from agriculture are difficult to control (Mandelker, 1989) and remain problematic even though these emissions dominate in terms of mass. For example, since 1995, NH_3 and N_2O in the EU have been reduced by less than 5% (Sutton *et al*., 2013), despite the above-mentioned policies for air pollution as well as the Kyoto Protocol (UNFCCC, 1994). Policy guidance on NH_3 reduction has so far been limited to `best-practice' measures, caps to fertilizer application rates and feeding strategies, evident in the United Nations Economic Commission for Europe (UNECE) framework code for good agricultural practice for reducing NH_3 (UN Economic and Social Council, 2001), in the UNECE Task Force on Reactive Nitrogen (Bittman *et al.*, 2014) and in the EU Council directive on N_2O (European Union, 2008; Galloway *et al.*, 2013; UNECE, 2005). Many `best practice' recommendations are practicable only for housed animals; for example (Bittman *et al.*, 2014), feeding strategies are difficult to carry out with grazing animals. Difficulties in dealing with a larger number of diverse actors for reducing agricultural NH_3 emissions (Amann *et al.*, 2013; Sutton *et al.*, 2013) translate directly into reduction targets: the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone envisaged a reduction of NO_x to 41% below 1990 levels, but only 17% for NH_3 in 1999 (UNECE, 1998). Fifteen years later, the EU's Sixth Environmental Action Programme's thematic strategy on air pollution (Amann *et al.*, 2013) lists targets of 60% (NO_x) and 27% (NH_3). In Denmark and the Netherlands, those non-point sources have been more strongly tackled using integrated abatement strategies accompanied by significant improvements of water quality and air pollution (Winiwarter *et al.*, 2015). Policies integrating supply chains across countries, covering all Nr species and also other compounds such as phosphorus and CO_2, are needed for the successful global reduction of Nr (Sutton *et al.*, 2013).

It is therefore clear that policies addressing nitrogen pollution must deal with consumption issues more than past treaties (Galloway *et al.*, 2014), and should aim for policy synergy (Sutton *et al.*, 2013). The analysis of anthropogenic footprints allows the evaluation of demand-side policy options (Hoekstra and Wiedmann, 2014) and emission shifting between countries (Kander *et al.*, 2015), and facilitates the transmission of information between firms and final consumers (O'Rourke, 2014). Given the intensification of international trade, such policies must also have a global coverage and reach. For this to happen, comprehensive information on the global flows of nitrogen compounds between pollution hotspots and centres of consumption must be available, and this is our study's main contribution. NFs share concepts and methods with CO_2, water and biodiversity footprints. Therefore, debates about countries' responsibility for the climate change impact of their imports apply equally to nitrogen: consumption-based nitrogen policy can enforce trade regulation, controls on nitrogen leakage, corporate reporting, certification and product labelling, just as demand-side abatement of carbon emissions, but it would also face the same obstacles in world trade agreements. Yet, the appeal of the NF is that it empowers consumers and shareholders to send strong preference signals along supply chains, and thus enables them to join producers in reducing nitrogen pollution.

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Chater 3: An improved methodology for calculating the nitrogen footprint of seafood

3.1 Abstract

Human activities create more reactive nitrogen than is created through natural processes every year. The excess reactive nitrogen in the environment causes various negative effects including eutrophication, climate change, acidification, and human health problems. The sources of the excess nitrogen are mainly fertilizers and animal and human waste generated by food production and consumption. Therefore, our food choices have major effects on the nitrogen load to the environment. To quantify the load, a consumption-based accounting tool, called the nitrogen footprint, has been recently developed. In current nitrogen footprint models, seafood is calculated as a single category using the same simple assumptions as livestock. However, there is a variety of types and methods of production of seafood. In addition, world per capita consumption of seafood is projected to continue expanding. In this paper, we propose a new nitrogen footprint model to evaluate the impact of seafood in detail, present the results of the model applied to Japan as a case study, and explain the important parameters that are needed to accurately evaluate the load of seafood consumption. Our model tracks the feeding steps in detail, considering differences among fed aquacultured seafood, non-fed aquacultured seafood (mainly bivalves and filter-feeding carp), and captured seafood. Our model evaluates the Japanese food nitrogen footprint of fed aquacultured seafood as 0.7 kg-N/capita/year, ca. 45% of that of all seafood, whereas the previous model evaluates it as 3.36 kg-N/capita/year. Our results demonstrate that the key factors for assessing the nitrogen load of seafood are the proportions of fed aquaculture and of plant protein in feed. In order to enable food choices that will effectively reduce nitrogen release, we provide the virtual N factors (per intake reactive nitrogen release during production) for different seafood as 0.2 (non-fed aquacultured and captured), 4.8 (freshwater and diadromous fish), 3.9 (demersal fish), 3.4 (pelagic fish and other marine fish), and 8.2 (crustaceans). Our results show that eating more non-fed aquacultured and captured seafood and less fed-aquacultured shrimps and prawns could reduce our nitrogen load from food consumption as effectively as choosing poultry instead of beef. Although its evaluation is limited to nitrogen load related to food itself and not including the load from energy use, etc., our detailed nitrogen footprint model for different seafood categories and production sources can quantify the effectiveness of policies and actions that link sustainable consumption and sustainable fisheries and aquaculture, contributing toward the Aichi Biodiversity Targets.

3.2 Introduction

Human activities have drastically changed the global nitrogen (N) cycle with the continuing creation of reactive N, denoted by N_r (Galloway *et al*., 2003, 2008). The term N_r includes all N compounds except N_2. Anthropogenic N_r has greatly increased with expanding food production, and total food production has increased with the growth of per capita food consumption in addition to population growth (Lavelle *et al*., 2005; Wood *et al*., 2005). On the other hand, the substantial amount of N_r released into the environment has caused adverse effects, including eutrophication, climate change, acidification, and human health problems (Canfield *et al*., 2010; Galloway *et al*., 2003). These N_r-related impacts, which are now recognized as major challenges for the world community (United Nations Conference on Sustainable Development, 2012; United Nations Environment Programme, 2014), are closely related to food consumption patterns (Lavelle *et al*., 2005; Wood *et al*., 2005).

In order to quantify how individual consumption contributes to the pressures on the environment, the concept of a "footprint" has been explored by many researchers since the idea of an ecological footprint (Rees, 1992; Wackernagel and Rees, 1996) was established in the 1990s. This initial concept was followed by the water footprint (Hoekstra and Hung, 2002) and the carbon footprint. The idea was further developed by Galli *et al*. (2012) to integrate a suite of footprints into the single conceptual framework of a "footprint family" to track human pressures comprehensively. Based on such consumption-based accounting, the N footprint, abbreviated to NF, has recently been introduced to quantify N_r released into the environment (Leach *et al*., 2012). To determine an individual's contribution to N_r release, a consumer-based NF model was developed by Leach *et al*. (2012), focusing on food production, food consumption and energy use. This model also made a step toward integrating N_r load into the footprint family.

Previous NF studies (Chatzimpiros and Barles, 2013; Gu *et al*., 2013; Leach *et al*., 2012, 2013; Leip *et al*., 2014; Shibata *et al*., 2014; Stevens *et al*., 2014) have pointed out that food production affects our N_r load. Moreover, Leach *et al*. (2012) highlighted that it is primarily affected by our choices of food items, such as type of meat and production methods. The NF of seafood (by which we mean both inland and marine "seafood", including finfish, mollusks, crustaceans, and their products) was included in the consumer-based NF model, but only as a single category with the assumption that aquaculture production is similar to livestock production and with the aquacultured ratio. While the model can take into account the differences between countries by modifying the parameters, e.g. the aquacultured ratio (Shibata *et al*., 2014), the information on categories of seafood (e.g. pelagic fish, crustaceans and cephalopods) and production systems (fed aquaculture, non-fed aquaculture and capture fisheries) has not yet been accurately provided. Non-fed aquacultured seafood (as for example used in Saurel *et al*., 2014 or Rana *et al*., 2009) refers to seafood produced by aquaculture systems where culture is predominately dependent on the natural environment for food, e.g. filter-feeding carp in fish ponds and clams planted in nursery beds. Although NF of seafood in a single category was presented as much as chicken for the same amount of protein consumed, some types of seafood may have high NF as beef in meat category, which is 2.5 times higher for production. Seafood contributed 6.4% of all supplied food protein globally, which is comparable to poultry meat (5.9%) and pork (5.8%) in the year 2009 (FAO, 2012a). In some fish-eating countries including Japan, fish is even more important for the choices of food. The simple evaluation for seafood may lead to misleading choices if there are significant differences among seafood types. Moreover, world per capita seafood consumption is projected to continue expanding at the annual growth rate of 0.6% during 2013–2022 (OECD/FAO, 2013). Since additional growth in fishery production will originate predominantly from aquaculture and aquaculture is increasing dependence on terrestrial crops and wild fish for feeds (Troell *et al*., 2014), NF of seafood may increase more than the increase in its production. Specific NF models for seafood will better help consumers and policy makers reduce N_r-related impacts arising from food choice. The NF models for seafood will also open the way to a better integration of N_r emission reduction into actions for sustainable fisheries and aquaculture from consumer-based perspective.

To provide adequate information for seafood, we have developed a new consumer-based NF model, which calculates NF of seafood for seven categories in two kinds of production systems (one for fed aquacultured and the other for non-fed aquacultured and captured). We then applied our model to Japan as a case study to provide a detailed analysis of NF of seafood. We also compared two sets of parameters to explore applicability of our model to countries other than Japan.

In this paper, we propose our detailed model of the NF of seafood. We also explain the important parameters needed to evaluate the N_r load of seafood consumption accurately using an application of the model to Japan. Finally, we discuss the need to assess seafood with a different approach from that used for livestock in developing indicators of the potential contribution of NF for sustainable food choices.

3.3 Materials and Methods

We defined NF the same as Leach *et al.* (2012), as the total amount of N_r released into the environment due to an entity's resource consumption, expressed in total units of N_r. In our calculation, however, we also include N_r lost in the production of captured seafood, which is transferred from water to land. The existing consumer-based NF model (Leach *et al.*, 2012) consists of two parts: food and energy. The food NF deals with loss from both N_r for crop/animal growth and its processing (food production NF) and N_r as a constituent of food (food consumption NF). The energy NF deals with N_r release from fossil fuel combustion. Here, we only focus on the food NF, especially for seafood, and do not consider non-food use or the energy NF related to food production. The reason for this is because the food NF forms the majority of the total NF and has direct links to our daily food choices.

In this section we first present the framework of our methodology, and then describe our model. Next, we describe the data used to estimate the parameters and the valuables in the model. Finally, we describe the calculations for comparing the importance of the parameters and the differences among the models and the parameter sets.

3.3.1 Framework of the Methodology

To evaluate the food NF of seafood for a country in comparison with the previous studies, we used FAO food supply data in seven categories for Japan for the year 2009 (FAO, 2012a) as an example dataset and applied two models: the common model and our model.

We first defined the common model the same as the model by Leach *et al.* (2012) except for the parameter set. We applied the common model with parameter set CM (Tables 3.1–3.5) based on the N_r flow common for both livestock and aquacultured seafood (including fed and non-fed) of all seven FAO categories (Figure 3.1a), where captured seafood is only accounted for food consumption NF (its flow is not shown). The food production NF of captured seafood was assumed to be negligible. Parameter set CM was modified from each *et al.* (2012) by replacing the N_r removal ratio for wastewater treatment system with 32%, as estimated for Japan by Oda and Masumoto (2006), used also for the other parameter sets (β_7 in Table 3.3). We changed the value to compare the two models with the case of Japan, because this effect of water treatment depends on the country's water treatment system, which varies, for example, from 5% for the United States of America (USA) to 78% for the Netherlands (Leach *et al*., 2012).

Table 3.1 Valuable and parameter definitions, units, references used in the nitrogen footprint models.

Variables	Description	Units	Reference
A_i, $A_{i(\text{fed-aq})}$, $A_{i(\text{nonfed-aq+captd})}$	Available nitrogen before step *i*, that of fed aquacultured seafood, and that of non-fed aquacultured and captured seafood	kg-N cap^{-1} yr^{-1}	Calculated (Eqs. (1)–(6))
B_i, $B_{i(\text{fed-aq})}$, $B_{i(\text{nonfed-aq+captd})}$	Available nitrogen added to step *i* that come from later steps or some steps in the flow of captured seafood of the same or other categories, that of fed aquacultured seafood, and that of non-fed aquacultured and captured seafood	kg-N cap^{-1} yr^{-1}	Calculated (Eqs. (7)–(9))
C_i, $C_{i(\text{fed-aq})}$, $C_{i(\text{nonfed-aq+captd})}$	Newly generated reactive nitrogen (new N_r) or reactive nitrogen transferred from water to land (transferred N_r) that is added to step *i*, that of fed aquacultured seafood, and that of non-fed aquacultured and captured seafood	kg-N cap^{-1} yr^{-1}	Calculated (Eqs. (10)–(11))
L_{domestic}, $L_{\text{domestic, fed-aq}}$	Domestic production of seafood in live weights and that of fed aquacultured seafood	Mg	FAO (2014a)
L_k^{ex}, L_k^{im}, L_k^{re}	Converted quantity of seafood commodity *k* exported from, imported to, and re-exported to the target region	Mg	Calculated ($L_k = T_k$ / θ_k)
L_{captd}, $L_{\text{fed-aq}}$, $L_{\text{nonfed-aq}}$	Use of captured, fed aquacultured, and of non-fed aquacultured seafood (in live weights)	Mg	FAO (2014a) (for parameter set W); Calculated (for parameter set J; Eq. (13))
L_{total}	Total seafood use in live weights (world production for parameter set W; domestic production and imported commodities minus exported commodities for parameter set J)	megagrams (Mg = 10^6 g; metric tons)	FAO (2014a) (for parameter set W); Calculated (for parameter set J; Eq. (14))
SFP	Quantity of supplied food protein	kg cap^{-1} yr^{-1}	FAO (2012a)
T_k^{ex}, T_k^{im}, T_k^{re}	Traded quantity of seafood commodity *k* exported from, imported to, and re-exported to the target region	Mg	FAO (2014a)
Parameters	**Description**	**Units**	**Reference**
α_i	Proportion of available nitrogen at step *i* that goes to the next step (the efficiency ratio at step *i*)	Unitless	Leach *et al.* (2012), Bouwman *et al.* (2013)
β_i	Proportion of unused nitrogen at step *i* that is changed back into N_2 (the removal ratio at step *i*)	Unitless	Leach *et al.* (2012), Oda and Matsumoto (2006)
γ_i	Proportion of unused and unremoved nitrogen at step *i* that is recycled (the recycle ratio at step *i*)	Unitless	Leach *et al.* (2012)
δ	Proportion of fed aquacultured seafood in all seafood supply (the fed aquaculture ratio)	Unitless	Calculated from FAO (2014a)
ε	Proportion of plant protein in the feed of the fed aquacultured seafood (the ratio of plant protein in feed)	Unitless	Calculated from FAO (2014a)
ζ	The ratio of offal to the entire input for seafood feed	Unitless	Tacon *et al.* (2011)
θ_k^{ex}, θ_k^{im}, θ_k^{re}	Live weight conversion ratio of commodity *k* (quantity of seafood commodity *k* to raw material used for its production) that is exported from, imported to, and re-exported to the target region	Unitless	FAO (2014c) with some calculated values (see caption of Appendix 2 Table B.3)
ρ_k^{ex}, ρ_k^{im}, ρ_k^{re}	Ratio of fed aquaculture in commodity *k* that is exported from, imported to, and re-exported to the target region	Unitless	Calculated from FAO (2014a)

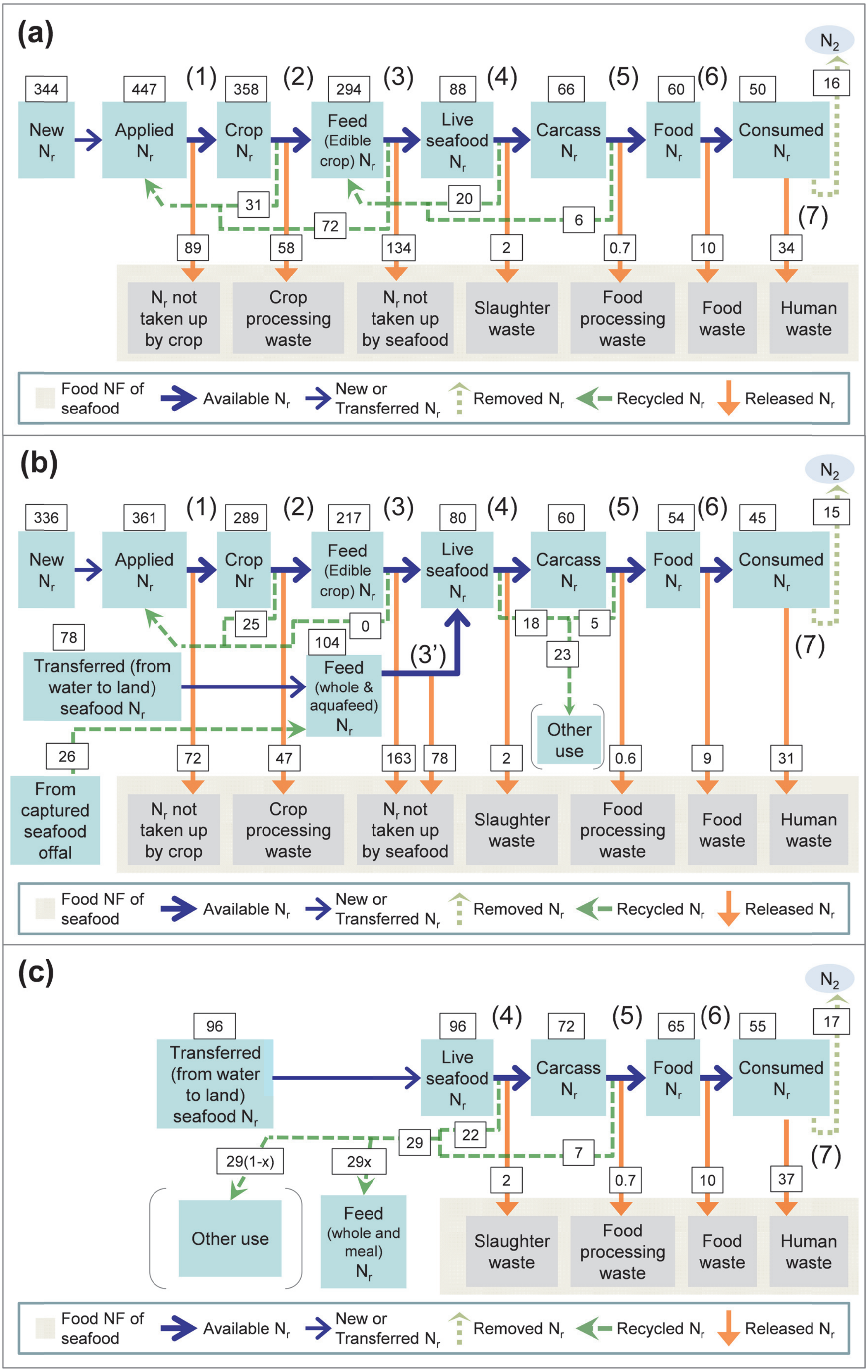
(a)
344
New Nr
447
Applied Nr
(1)
358
Crop Nr
(2)
294
Feed (Edible crop) Nr
(3)
88
Live seafood Nr
(4)
66
Carcass Nr
(5)
60
Food Nr
(6)
50
Consumed Nr
N2
16
(7)
31
72
20
6
89
58
134
2
0.7
10
34
Nr not taken up by crop
Crop processing waste
Nr not taken up by seafood
Slaughter waste
Food processing waste
Food waste
Human waste
Food NF of seafood
Available Nr
New or Transferred Nr
Removed Nr
Recycled Nr
Released Nr
(b)
336
New Nr
361
Applied Nr
(1)
289
Crop Nr
(2)
217
Feed (Edible crop) Nr
(3)
80
Live seafood Nr
(4)
60
Carcass Nr
(5)
54
Food Nr
(6)
45
Consumed Nr
N2
15
(7)
78
Transferred (from water to land) seafood Nr
25
0
104
Feed (whole & aquafeed) Nr
(3')
18
5
23
Other use
26
From captured seafood offal
72
47
163
78
2
0.6
9
31
Nr not taken up by crop
Crop processing waste
Nr not taken up by seafood
Slaughter waste
Food processing waste
Food waste
Human waste
Food NF of seafood
Available Nr
New or Transferred Nr
Removed Nr
Recycled Nr
Released Nr
(c)
96
Transferred (from water to land) seafood Nr
96
Live seafood Nr
(4)
72
Carcass Nr
(5)
65
Food Nr
(6)
55
Consumed Nr
N2
17
(7)
29
22
7
29(1-x)
29x
Other use
Feed (whole and meal) Nr
2
0.7
10
37
Slaughter waste
Food processing waste
Food waste
Human waste
Food NF of seafood
Available Nr
New or Transferred Nr
Removed Nr
Recycled Nr
Released Nr

Figure 3.1 Reactive nitrogen (N_r) flows in seafood production processes. (a) The common flow for livestock and aquacultured seafood in the nitrogen footprint (NF) model by Leach *et al*. (2012), originally designed for the USA as a representative for industrial food production facilities that are common in developed countries. (b) The flow for fed aquacultured seafood in our model. (c) The flow for non-fed aquacultured seafood and captured seafood in our model. Bold, thin, and dashed arrows indicate input from the stage before a numbered step. Pale arrows from the stages indicate released and removed Nr. The values shown are all for providing 100 units of total N_r consumption, using (a) the common model with parameter set CM, and (b) and (c) our model with parameter set W (global average case). The flow (a) is common for all seafood categories with the aquacultured ratio of 50%. The shown 50 units from aquacultured seafood together with 50 units from captured seafood (not shown and considered to have a negligible food production NF) provide 100 units (Consumed N_r = 50 + 50 = 100). The flows (b) and (c) are for crustaceans with the aquacultured ratio of 45%, which altogether provide 100 units (Consumed N_r = 45 + 55 = 100). Food NF of seafood equals the total released N_r. As a result of rounding, the total sum of values at each step may not be equal to the values at the previous stage

Table 3.2 The efficiency ratios at production/consumption steps used to calculate food nitrogen footprint for the Japan case.

Category of food	Proportion of previous available nitrogen that makes it into the next step (α)							
	step 1 (Crop uptake/loss)	step 2 (Crop processing)	step 3 (Feed consumption (plant-based))	step 3' (Feed consumption (seafood-based))	step 4 (seafood dissection)	step 5 (food processing)	step 6 (food consumption/ waste)	step 7 (sewage treatment)
Seafood	80%	75%	See Table 3.4	See Table 3.4	75%	90%	84%	-
Poultry	82%	75%	45%	-	75%	90%	84%	-
Pigmeat	82%	75%	35%	-	75%	90%	84%	-
Beef	82%	80%	20%	-	75%	90%	84%	-
Milk	82%	85%	25%	-	98%	98%	68%	-
Vegetables	20%	75%	-	-	-	75%	75%	-
Starchy roots	87%	75%	-	-	-	75%	75%	-
Legumes	90%	75%	-	-	-	95%	84%	-
Grains	80%	75%	-	-	-	95%	68%	-

Note: Values for seafood shown here (except for steps 3 and 3') are commonly used for all parameter sets. Values for food categories other than seafood are defined as parameter set CM as the only set used for the calculation for those food categories. All values except for steps 3 and 3' of seafood are taken from Leach *et al*. (2012), who determined them originally for the virtual N factor calculations for the USA as representative values for industrial food production facilities that are common in developed countries.

Table 3.3 The ratios of removal and recycling at production/consumption steps used to calculate food nitrogen footprint for the Japan case.

Category of food	Proportion of unused nitrogen removed as N_2 (β)		Proportion of unused and unremoved nitrogen that is recycled (γ)							
	step 1–6 & 3′	step 7	step 1 (Crop uptake/ loss)	step 2 (Crop processing)	step 3 (Feed consumption (plant-based))	step 3′ (Feed consumption (seafood-based))	step 4 (seafood dissection)	step 5 (food processing)	step 6 (food consumption/ waste)	step 7 (sewage treatment)
Seafood	0%	32%[a]	0%	35%	see Table 3.4	see Table 3.4	90%	90%	0%	0%
Poultry	0%	32%[a]	0%	35%	35%	-	90%	90%	0%	0%
Pork	0%	32%[a]	0%	35%	35%	-	90%	90%	0%	0%
Beef	0%	32%[a]	0%	35%	35%	-	90%	90%	0%	0%
Milk	0%	32%[a]	0%	35%	35%	-	90%	90%	0%	0%
Vegetables	0%	32%[a]	0%	35%	-	-	-	15%	0%	0%
Starchy roots	0%	32%[a]	0%	35%	-	-	-	15%	0%	0%
Legumes	0%	32%[a]	0%	35%	-	-	-	15%	0%	0%
Grains	0%	32%[a]	0%	35%	-	-	-	15%	0%	0%

Note: Descriptions for the steps for β are the same as that for γ. Values for seafood shown here (except for steps 3 and 3') are commonly used for all parameter sets. Values for food categories other than seafood are defined as parameter set CM as the only set used for the calculation for those food categories. Unless otherwise indicated, values are taken from Leach *et al.* (2012), who determined them originally for the virtual N factor calculations for the USA as representative values for industrial food production facilities that are common in developed countries.

[a] Estimated average ratio for water treatment in Japan (Oda and Matsumoto, 2006).

Table 3.4 The ratios of efficiency and recycling used to calculate food nitrogen footprint for the Japan case.

Category of seafood (FAOSTAT group)	(3) & (3′) feed consumption step					
	Efficiency ratio (α)			Recycling ratio (γ)		
	Parameter set CM [a]	Parameter set W [b]	Parameter set J [b]	Parameter set CM [a]	Parameter set W [c]	Parameter set J [c]
Freshwater and diadromous fish	30%	36%	36%	35%	0%	0%
Demersal fish	30%	36%	36%	35%	0%	0%
Pelagic fish	30%	36%	36%	35%	0%	0%
Marine fish, other	30%	36%	36%	35%	0%	0%
Crustaceans	30%	25%	25%	35%	0%	0%
Cephalopods	30%	-	-	35%	-	-
Mollusks, other	30%	-	-	35%	-	-

Note: All mollusks, including "cephalopods" and "mollusks, other", were considered to be non-fed aquaculture and capture fisheries. "Marine fish, other" is "marine fish not identified" in FAO (2014a). Parameter set CM is based on the reactive nitrogen flow common for both livestock and aquacultured seafood, modified from Leach *et al.* (2012) by replacing the removal ratio of reactive nitrogen for wastewater treatment system shown in

Table 3.3. Parameter set W is designed as a world average parameter set for the composition of the seafood categories. Parameter set J is designed, considering traded commodities, as a country-specific parameter set based on the species/commodities composition of each FAO category consumed in Japan.

[a] Leach *et al*. (2012).

[b] Estimated complement of the retention of nitrogen in finfish and crustacean production by Bouwman *et al*. (2013).

[c] Deduced from the fact that ordinary aquaculture farms do not recycle reactive nitrogen from bottom sediment.

Table 3.5 The ratios of fed aquacultured seafood, plant protein in feed, and recycling used to calculate food nitrogen footprint for the Japan case.

Category of seafood (FAOSTAT group)	Ratio of fed aquacultured seafood (δ)			Ratio of plant protein in feed			Ratio of fish meal derived from fisheries by-products (ζ)	
	Parameter set CM [a]	Parameter set W [b]	Parameter set J [b]	Paramete r set CM [c]	Parameter set W [d]	Parameter set J [d]	Parameter set CM	Parameter sets W and J [e]
Freshwater and diadromous fish	50%	60%	58%	91%	54%	34%	-	25%
Demersal fish	50%	6%	5%	91%	19%	0%	-	25%
Pelagic fish	50%	1%	6%	91%	0%	0%	-	25%
Marine fish, other	50%	5%	5%	91%	0%	0%	-	25%
Crustaceans	50%	45%	50%	91%	68%	53%	-	25%
Cephalopods	50%	0%	0%	91%	-	-	-	25%
Mollusks, other	50%	0%	0%	91%	-	-	-	25%

Note: All mollusks, including “cephalopods” and “mollusks, other”, were considered to be non-fed aquaculture and capture fisheries. “Marine fish, other” is “marine fish not identified” in FAO (2014a). Parameter set CM is based on the reactive nitrogen flow common for both livestock and aquacultured seafood, modified from Leach *et al*. (2012) by replacing the removal ratio of reactive nitrogen for wastewater treatment system shown in Table 3.3. Parameter set W is designed as the world average parameter set for the composition of the seafood categories. Parameter set J is designed, considering traded commodities, as a country-specific parameter set based on the species/commodities composition of each FAO category consumed in Japan.

[a] Estimated from the calculation in Leach *et al*. (2012).

[b] Estimated from the 2009 data in FAO (2014a).

[c] Calculated from the ratios of previous nitrogen available (α_2) and recycled nitrogen (B_3) in Leach *et al*. (2012).

[d] Estimated ε from the 2009 data in FAO (2014a), with feed ingredient usage from Tacon *et al*. (2011) and protein percentage from Córdova-Murueta and García-Carreño (2002), Raven and Walker (1980) and FAO Fishery Industries Division (1986).

[e] Tacon *et al*. (2011).

The other parameters of CM were determined originally for the USA as representative values for industrial food production facilities that are common in developed countries. In the Nr flows of Figure 3.1, we present the values for providing 100 units of total seafood N consumption, not the introduction of 100 units of N_r into the system as in Leach *et al*. (2012) because we focus on the commodity composition of the consumption basket. In the case of Figure 3.1a, reflecting the aquacultured ratio of 50% (δ for CM in Table 3.5), 50 units of aquacultured seafood and 50 units of captured seafood (the flow of the latter is not shown) are consumed.

We devised a new model (Section 3.3.2) with the two sets of parameters J and W (Tables 3.1–3.5 and Section 3.3.3) based on a set of two N_r flows for different sources of all seven FAO seafood categories (Figure 3.1b for fed aquacultured and Figure 3.1c for non-fed aqua-cultured and captured). Parameter set J is designed, considering traded commodities, as a country-specific parameter set based on the species/commodities composition of each FAO category consumed in the target region, in this case Japan, whereas parameter set W is designed as the world average parameter set, for the composition of each seafood category. The parameters for J and W are different in the fed aquaculture ratio and the ratio of plant protein in feed (Table 3.5). In the flows of Figure 3.1b and c, we present the values for providing 100 units of seafood N_r consumption for the case of crustaceans with parameter set W, where 45 units of fed aquaculture seafood (δ= 45% for crustaceans with W in Table 3.5) and 55 units of non-fed aquacultured and captured seafood are consumed. We assumed the flows of each category of food not exchanging with each other as in Leach *et al*. (2012), e.g. offal of livestock does not go to the flow of fed aquacultured seafood. (We present values for the Nr flows of seafood categories for all parameter sets not shown in Figure 3.1 as online supplementary data at http://dx.doi.org/10.1016/j.ecolind.2015.08.039).

To calculate the food NF of items other than seafood, we only applied the common model with the parameter set CM to the same food supply data given by the FAO (2012a) in its food balance sheet data for Japan for the year 2009.

The importance of consistent system boundaries and the effect of truncation errors have been discussed comparing the bottom-up and the top-down approaches in recent footprint work (e.g. Feng *et al*., 2011; Lenzen, 2000; Suh *et al*., 2004). We use the bottom-up approach for food NF similar to Leach *et al*. (2012), because food NF evaluates direct loss of N_r from food protein or its source, but not indirect emission of N_r from fossil fuel for food production. Suh *et al*. (2004) pointed out the incompleteness of the emissions data from small-to-medium-sized enterprises and nonpoint sources for the bottom-up approach. In order to eliminate such incompleteness in registered emissions data, we used the parameters of ratios referring literature to estimate the N_r lost during the production steps. Feng *et al*. (2011) demonstrated that the substantial differences between the bottom-up and the top-down approaches were caused by a large proportion of agricultural water use consumed by industrial sectors for production inputs based on top-down approaches. In our model, as shown in Figure 3.1b and c, we focus on consumption quantities and capture the upstream of food protein N_r, which is not usually lost indirectly outside of our framework. The remaining truncation errors would occur in the following three steps: production of N fertilizers, production of feed derived from seafood, and process toward "other use" of offal. The production of N fertilizers is not included in the calculation for consistency with the existing model. The loss in production of feed derived from seafood is negligible, considering the fact all protein in the ground whole fish or fish offal is utilized in fishmeal in majority of cases (Bechtel, 2005). The loss included in the "other use" is assumed to be small for food as N_r-intensive commodities, similarly to the energy-intensive commodities reported to achieve system completeness of 90% at lower order of production by Lenzen (2000).

3.3.2 Development of the New Model

We evaluate seven basic steps and one additional step between the production and consumption stages: (1) crop uptake/release of applied N_r, (2) crop processing (3) consumption of plant-based feed, (3) consumption of seafood-based feed, (4) seafood dissection, (5) food processing, (6) food consumption/waste, and (7) sewage treatment (Figure 3.1b and c). As shown in the conceptual figure (Figure 3.2; see Table 3.1 for the description of symbols), at the step *i*, "available Nr" (A_i) moves on to the next step with the efficiency ratio α_i, together with "recycled N_r" from other steps or another flow (denoted by B_{i+1}). At the beginning of the flow, "new N_r" or "transferred N_r" (transferred by human from water to land) is also added to step *i* (denoted by C_i). The unused N_r ($(1-\alpha_i)A_i$) is partly changed back into N_2 as "removed N_r" by wastewater treatment plant with the removal ratio β_i . The other part of the N_r ($(1-\alpha_i)(1-\beta_i)A_i$) is transferred as "recycled N_r" with the recycling ratio γ_i to a previous step in the flow of the same or other categories of fed aquacultured seafood, or to other uses (mainly feed for livestock). The rest of the

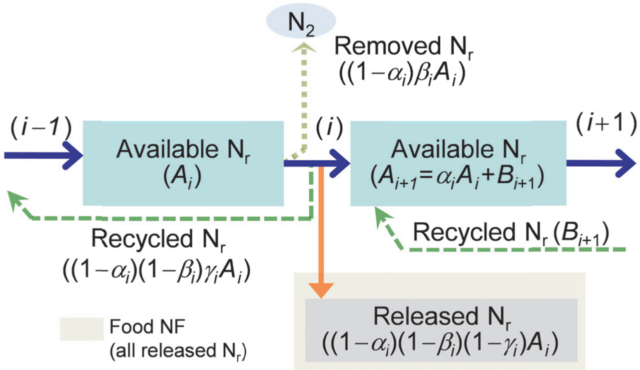

Figure 3.2 Conceptual figure of the models for food nitrogen footprint calculation. Available N_r before step *i* (A_i) goes to the next step at the efficiency ratio α_i ($\alpha_i A_i$, part of available N_r at step *i* + 1). The unused N_r ($(1-\alpha_i)A_i$) become N_2 at the removal ratio β_i (removed N_r). The other part of N_r ($(1-\alpha_i)(1-\beta_i)A_i$) is recycled at the recycling ratio γ_i (recycled N_r). The rest of N_r ($(1-\alpha_i)(1-\beta_i)(1-\gamma_i)A_i$) is released (released N_r). The sum of released N_r from all steps equals to food nitrogen footprint. New or transferred N_r becoming a part of A_1, $A_{3'}$ or $A_{4(\text{nonfed-aq+captd})}$ is not shown.

N_r ($(1-\alpha_i)(1-\beta_i)(1-\gamma_i)A_i$) is unintendedly discharged as "released N_r" into the environment and is summed up as food NF ($\Sigma_i(1-\alpha_i)(1-\beta_i)(1-\gamma_i)A_i$).

We added step (3′) in Figure 3.1b because aquacultured seafood feed on animal protein, which is mostly seafood protein, as well as plant protein from step 2 (see Table 3.5). For the ratio of offal to the entire input for seafood feed (ζ in Tables 3.5), we assumed 25% following Tacon *et al.* (2011), who considered the majority of fed aquaculture feed to be fishmeal. The N_r flow for non-fed aquacultured and captured seafood (Figure 3.1c) starts at step 4, and the recycled N_r from steps 4 and 5 was assumed to become mainly feed for fed aquacultured seafood. We put *x* for the ratio used as feed, because seafood offal of one category is not used only for the same category, but used also for other seafood categories (e.g. freshwater and diadromous fish does not have enough offal to feed within the same category) and used for other uses including feed for livestock, fertilizer, and waste.

We start calculation from supplied food protein (*SFP*) of each category of seafood with the aquacultured ratio δ, assuming that *SFP* includes 16% N from general knowledge, following Leach *et al.* (2012). Our model can be described as follows (see Section 3.3.3 for further details of the parameters):

$$A_{6(\text{fed-aq})} = SFP \times 0.16 \times \delta, \quad (1)$$

$$A_{6(\text{nonfed-aq+captd})} = SFP \times 0.16 \times (1 - \delta) \quad (2)$$

$$A_i = (A_{i+1} - B_{i+1}) \,/\, \alpha_i, \ (i \neq 3, 3', 6, 7) \quad (3)$$

$$A_3 = (\varepsilon / \alpha_3) A_{4(\text{fed-aq})}, \quad (4)$$

$$A_{3'} = ((1 - \varepsilon)/\alpha_{3'}) A_{4(\text{fed-aq})} \quad (5)$$

$$A_7 = \alpha_6 A_6 \quad (6)$$

$$B_i = 0, \ (i \neq 1, 3') \quad (7)$$

$$B_1 = (1 - \alpha_2)(1 - \beta_2)\gamma_2 A_2 + (1 - \alpha_3)(1 - \beta_3)\gamma_3 A_3, \quad (8)$$

$$B_{3'} = \zeta A_{3'}, \quad (9)$$

$$C_i = 0, \ (i \neq 1, 3', 4_{(\text{nonfed-aq+captd})}), \quad (10)$$

$$C_i = A_i - B_i, \ (i = 1, 3', 4_{(\text{nonfed-aq+captd})}). \quad (11)$$

The aquacultured ratio δ is an estimated value for each category in the target region with the calculation of production in live weights ($L_{\text{fed-aq}}$, L_{total}) as follows. Since the ratio of fed aquacultured seafood to total seafood in production is nearly equal to that in food use,

$$\delta \approx L_{\text{fed}} / L_{\text{total}} \quad (12)$$

where $L_{\text{total}} = L_{\text{fed}} + L_{\text{non-fed-aq}} + L_{\text{captd}}$.

For parameter set W, we can estimate δ with the fed aquaculture production quantity and the total production quantity in the world in each category given by FAO (2014a), and no further calculation is required (see Section 3.3.3, Appendix 2.2.1.1 and Appendix 2 Table B.1 for further details).

For parameter set J, δ for the target region can be estimated with the quantity for domestic use, defined as domestic production plus import minus export. We use the live weight conversion ratio (θ_k) and the fed aquaculture ratios (ρ_k^{im}, ρ_k^{ex}, and ρ_k^{re}) to calculate the live weights for raw materials needed to produce the quantity of traded commodity k (T_k). The quantities of fed aquaculture and the total production in Eq. (12) for each category are as follows (see Section 3.3.3 and Appendix 2.2.1.2 for further details):

$$L_{\text{fed-aq}} = L_{\text{domestic, fed-aq}} + \Sigma_k \rho_k^{\text{im}} L_k^{\text{im}} - (\Sigma_k \rho_k^{\text{ex}} L_k^{\text{ex}} + \Sigma_k \rho_k^{\text{re}} L_k^{\text{re}})$$

$$= L_{\text{domestic, fed-aq}} + \Sigma_k \rho_k^{\text{im}} T_k^{\text{im}} / \theta_k - (\Sigma_k \rho_k^{\text{ex}} T_k^{\text{ex}} / \theta_k + \Sigma_k \rho_k^{\text{re}} T_k^{\text{re}} / \theta_k), \quad (13)$$

$$L_{\text{total}} = L_{\text{domestic}} + \Sigma_k L_k^{\text{im}} - (\Sigma_k L_k^{\text{ex}} + \Sigma_k L_k^{\text{re}})$$

$$= L_{\text{domestic}} + \Sigma_k T_k^{\text{im}} / \theta_k - (\Sigma_k T_k^{\text{ex}} / \theta_k + \Sigma_k T_k^{\text{re}} / \theta_k), \quad (14)$$

3.3.3 Data Description and Assumptions

To improve the accuracy of the NF model for seafood, we mainly investigate parameters related to the feed consumption step of steps 3 and 3′ in parameter sets J and W (α_3, γ_3, δ, ε and ζ in Tables 3.4 and 3.5) and also the effect of water treatment (β_7 in Table 3.3). For the other steps, although efficiency and recycling ratios (α_i and γ_i) are potentially different for each category in the target region, we assume the same production methods for all categories for all countries, using the parameters by Leach *et al*. (2012). We focus on the feeding steps because, in the common model's calculation shown in Figure 3.1a, N_r release in step 3 ($(1-\alpha_3)(1-\beta_3)(1-\gamma_3)A_3$ = 134) contributed 41% of total food NF of seafood ($\Sigma_i(1-\alpha_i)(1-\beta_i)(1-\gamma_i)A_i$ = 327.7). This is the largest of the seven steps, followed by 27% at step 1 and 18% at step 2.

For the feeding efficiency (α_3), the aquaculture waste recycling ratios (γ_3), and the conversion ratios of commodities (θ), we assume the same ratios for all producing regions because it depends more on species. For the fed aquaculture ratio (δ) and the ratio of plant protein in feed (ε), we assume the different ones for each species, and resulting differences in regions.

We estimate δ from production and trade data in weight in FishstatJ (FAO, 2014a). Detailed results of the calculation for the domestic use for Japan are shown in Appendix 2 Table B.2. We consider mollusks (cephalopods and "mollusks, other") to be "non-fed aquaculture and capture fisheries", because cephalopods are all captured, and most of seafood included in "mollusks, other" are bivalves (Bivalvia), which are captured or non-fed aquacultured seafood. In addition, it is difficult to obtain reliable data for N_r included in each species of fed aquacultured shellfish because shell weight is included in the catch amount.

To estimate the fed aquaculture ratio for imported commodity *k* (ρ_k^{im}), we first find out the main importing partners that account for ≥90% of the total import, for the Japan case from the data given by Ministry of Finance of Japan (2010). Next, we calculate the fed aquaculture ratio of raw material species for each of the producing countries from the FishstatJ production data of the country with Eq. (12), assuming the ratio is the same for domestic use and exports. We then calculate ρ_k^{im} as a weighted average of each of these ratios based on traded weights to Japan. If a producing country accounted has a large amount of re-export, the main originally producing countries' ratios should also be used for the estimation, of which we did not find any for the Japan case. For exported commodity k from Japan, the ratio ρ_k^{ex} is calculated from the FishstatJ production data of Japan with Eq. (12). For the Japan case, the amount of re-exported commodities (T_k^{re}) was zero. If the target region has some amount of re-exported commodity k, the ratio ρ_k^{re} is assumed to be the same as ρ_k^{im}. We explain further details of the calculation of δ in Appendix 2.2.1.2, including conversion ratios θ_k (Appendix 2 Table B.3) and the fed aquaculture ratios ρ_k^{im} and ρ_k^{ex} for each commodity (Appendix 2 Table B.4).

The ratio of plant protein in feed ε is an average of estimated ratios for each of the species groups in each category, weighted by fed aquacultured production in live weights (Appendix 2 Table B.5). The ratio for a species group is estimated as a weighted average of the ratios for each of the main producing countries (the target region, in this case Japan, and its main importing partners as described above). The species groups taken into account are the major species that make up over 90% of the total production in live weight in the world (parameter set W) or of the domestic use in live weights in the target region (parameter set J).

3.3.4 Comparison of Parameters and Models

To explore the importance of model parameters, we examined the four parameters α, γ, δ, and ε at steps 3 and 3′ for the case of Japan. Using our model, we changed the parameters from parameter set CM to parameter set W/J one at a time and then calculated food NF of seafood for Japan and the ratio of the change from the common model's evaluation.

To compare the differences between models in assessing the load of each category of seafood, we calculated, for each model, the ratio of "total N_r released to the environment in the production processes from steps 1 to 6 (the entire food NF of seafood minus human waste in Figure 3.1)" over "N_r in human intake (consumed N_r in Figure 3.1)", what Leach *et al*. (2012) called the "Virtual N Factor". Higher values signify more N_r has been released to the environment as a virtual N_r flow for the same amount of human intake.

3.4 Results

In the studied year of 2009, the overall amount of seafood protein supplied in Japan accounted for 41% of animal protein and 23% of all protein (FAO, 2012a). As food N_r in

Figure 3.1, the per capita food protein supplied per year included a total of 1,221 g-N: 105 g-N in freshwater and diadromous, 210 g-N in demersal fish, 491 g-N in pelagic fish, 181 g-N in "marine fish, other" (unidentified marine fish as in FAO, 2012a), 88 g-N in crustaceans, 111 g-N in cephalopods, and 35 g-N in other mollusks.

To assess the N_r load of the seafood consumption, in this section we first present the quantifications of food NF of seafood for the Japan case by the two models. Next we describe the sensitivity of each aspect of the flow to changes of the parameters of the NF models. Finally we give the "per intake N_r released to the environment in production" (virtual N factor) of each category for the different models and parameter sets.

3.4.1 Quantification of the NF by Seafood Category

The overall average of per capita food NF of seafood for the Japan case was evaluated as 3.71 kg-N/year with the common model, which was halved to 1.53 kg-N/year with parameter set W and to 1.55 kg-N/year with parameter set J when evaluated with our model (Figure 3.3). Since the per capita NF of other food categories was 13.46 kg-N/year for all models and parameter sets, NF of seafood was about 10% of the total food NF in our model. In our model, more than half of the total NF of seafood was due to non-fed aquacultured and captured seafood. Focusing on fed aquacultured seafood, the NF for that was reduced by about 80% compared with the common model calculation. This significant difference of NF was primarily due to the evaluations for categories of mollusks and marine seafood, including demersal fish, pelagic fish, and "marine fish, other" (Figure 3.4). On the other hand, NFs of seafood with the two sets of parameters in our model were quite similar in both composition and value in most of the categories, being somewhat different for only pelagic and demersal fish.

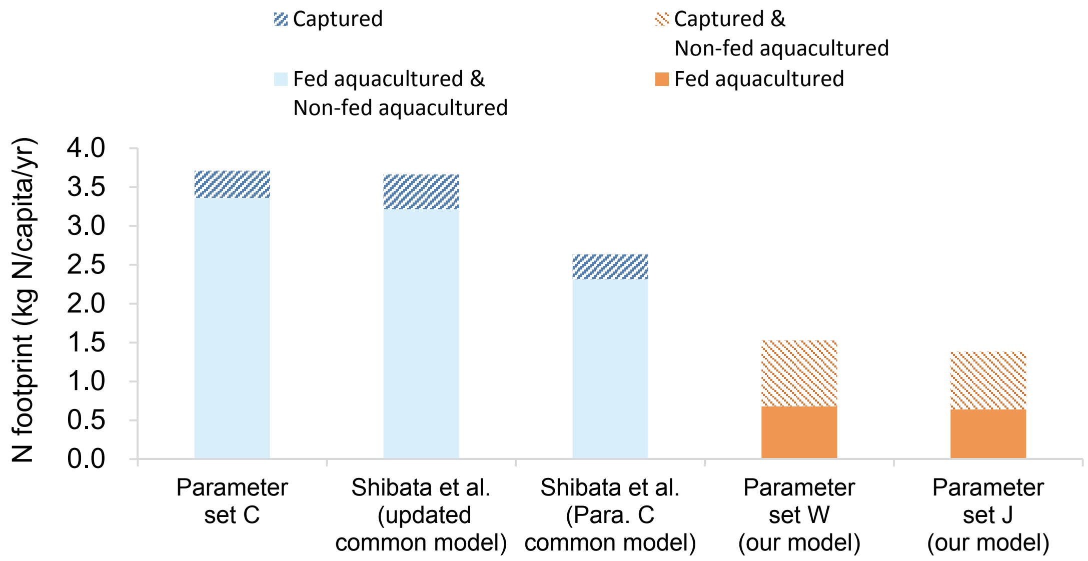

Figure 3.3 Comparisons of per capita food nitrogen footprints (NFs) of seafood for the Japan case calculated with the two models. The common model is applied with parameter set CM. Parameter set W is designed for global average, and parameter set J is specific to Japan. Food NF includes both production NF and consumption NF. Shibata *et al.* (2014) is calculated with the assumption of "Japan with trade", which consider the aquacultured rate and self-sufficiency rate and for Japan, assuming all trade associated with the USA.

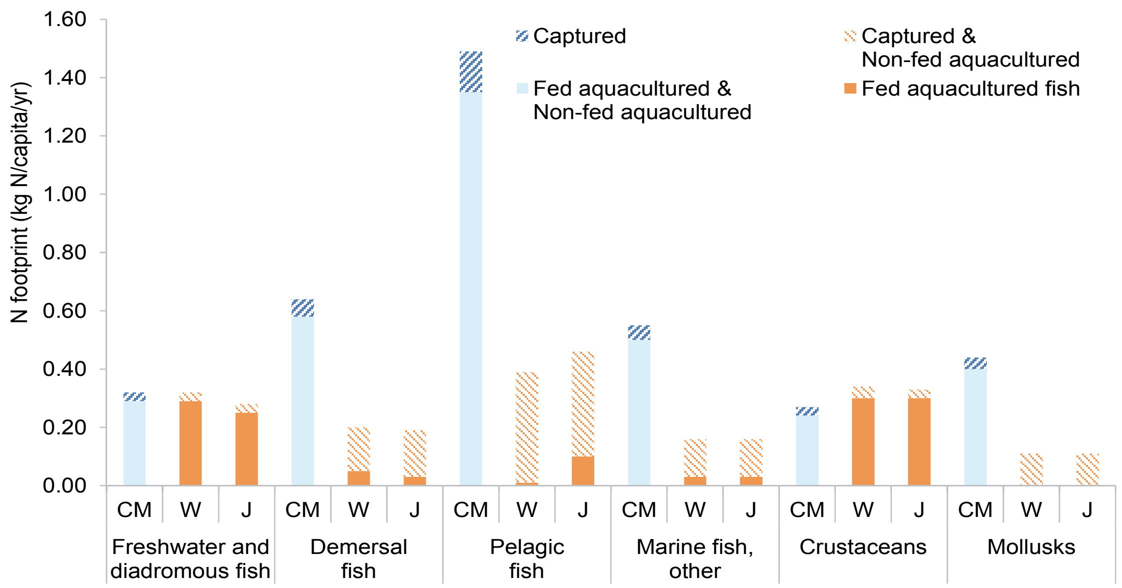

Figure 3.4 Per capita food nitrogen footprints (NFs) of seafood categories for the Japan case calculated with the two models. CM: the common model with parameter set CM, W: our model with parameter set W (global average), J: our model with parameter set J (specific to Japan). Food NF includes both production NF and consumption NF. Cephalopods and other mollusks are both included in category of mollusks.

3.4.2 Examination of the Model Parameters for the Feed Consumption Process

Among the all changes made to values of parameter set CM at the feed consumption steps (steps 3 and 3'), only the change of the recycling ratio to zero raised food NF for fed aquacultured seafood from that of the common model evaluation for the Japan case (Table 3.6). On the other hand, changes in the fed aquacultured seafood ratio and plant protein feed ratio significantly lowered the NF evaluation. Although relatively lower feeding efficiency (α) increases NF of seafood to some extent, feeding needs, type of protein in feed, and the recycling ratio have substantially larger influences.

Table 3.6 Changes of parameters being made to parameter set CM and quantification for fed aquacultured seafood.

Parameter that is changed	Food nitrogen footprint (production + consumption) [kg-N/capita/year]	Ratio of change
No change from parameter set CM	3.36	-
Efficiency ratio (α)	2.92	-13%
Recycling ratio (γ)	4.10	+22%
Ratio of fed aquacultured seafood (δ)		
Parameter set W	0.70	-79%
Parameter set J	0.83	-75%
Ratio of plant protein in feed (ε)		
Parameter set W	1.41	-58%
Parameter set J	1.30	-61%

Note: See Tables 3.4 and 3.5 for the original and changed parameter values.

3.4.3 Examination of Reactive Nitrogen Release in Production Processes

With both parameter sets our model generally estimated smaller N_r release during fed aquacultured seafood production compared with the common model, as shown by the lower virtual N factors in Table 3.7. Values that are not for the weighted averages can be applied to the cases in other years or other regions. In contrast, our model with both parameter sets estimated larger virtual N factors for fed aquacultured crustaceans and non-fed seafood (Figure 3.5 for the case of parameter set W). Moreover, the differences between the two parameter sets used with our model do not make a significant difference to the evaluation.

The virtual N factors for other categories of foods were common in the two models, and were set equal to those of Leach *et al*. (2012): beef, 8.5; milk, 5.7; pork, 4.7; poultry, 3.4; vegetables, 10.6; starchy root, 1.5; grains, 1.4; and legumes, 0.7. With our model, the values for seafood in different categories differed significantly from that of captured seafood, less than legumes, to that of fed aquacultured crustaceans, the same level as beef.

Table 3.7 Comparison of the nitrogen footprint models and parameter sets for reactive nitrogen release during production.

Category of seafood (FAOSTAT group)	Virtual N factor (reactive N loss in production / N intake)			N intake in protein (A_6) allocated for the Japan case [kg-N/capita/year]		
	Leach *et al.* (2012)	Parameter set W	Parameter set J	Leach *et al.* (2012)	Parameter set W	Parameter set J
Seafood	3.0 [a]	0.8 [a]	0.8 [a]	1.025	1.025	1.025
Non-fed	0.0	0.2	0.2	0.513	0.918	0.899
Fed aquacultured	5.9 [c]	5.6 [a]	5.0 [a]	0.513	0.107	0.126
Freshwater and diadromous fish	5.9 [b]	4.8	4.3	0.044	0.053	0.051
Demersal fish	5.9 [b]	3.9	3.4	0.088	0.010	0.008
Pelagic fish	5.9 [b]	3.4	3.4	0.206	0.003	0.023
Marine fish, other	5.9 [b]	3.4	3.4	0.076	0.007	0.007
Crustaceans	5.9 [b]	8.2	7.6	0.037	0.033	0.037

Note: Virtual N factor is the ratio of "reactive nitrogen released to the environment in the processes of steps 1–6" over "reactive nitrogen in human intake". "Marine fish, other" is "marine fish not identified" in FAO (2014a). Values that are not for the weighted averages are for general calculation that can be applied to other cases. As a result of rounding values, sub totals and totals of categories may not equal sums of values for lower categories.

[a] Value for the weighted averages with the consumed quantities.

[b] Calculated for higher categories.

[c] Including "cephalopods" and "mollusks, other" as fed aquacultured seafood.

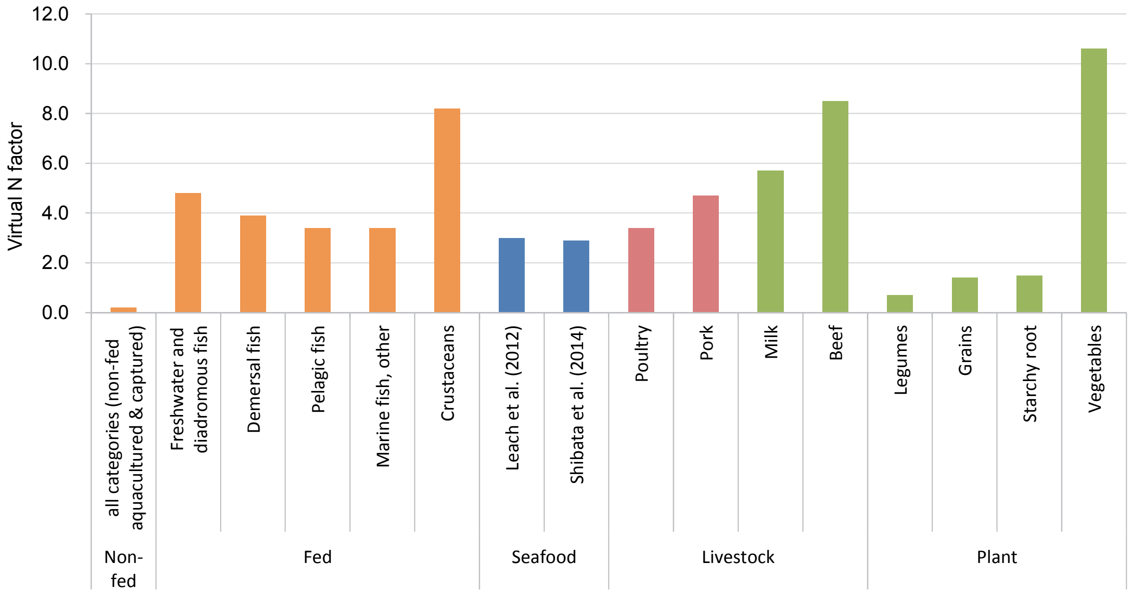

Figure 3.5 Virtual N factors of seafood for different categories and production sources. Virtual N factor is the ratio of "reactive nitrogen released to the environment in the production and processing processes" over "reactive nitrogen in human intake". The values can be used as the world average case (calculated by our model with parameter set W). The virtual N factor from Shibata *et al*. (2014) is with the assumption of "Japan with trade".

3.5 Discussion

In an effort to quantify N_r load from seafood consumption accurately and in detail, we developed a new NF model for seven categories of seafood and two kinds of production, and applied the model to Japan as a case study. The results of our model (Figure 3.3) lie within the range of N_r eutrophication potentials for seafood calculated by Xue and Landis (2010) using the life cycle assessment (LCA) method, which is 1.1–3.7 kg-N/capita/year with Japanese seafood consumption of 56.6 kg/capita/year. Their calculation includes both aquacultured and captured seafood in unknown proportions, together with a negligible portion coming from energy use. The somewhat lower estimation of our model shows the previous common model for consumers (Leach *et al*., 2012) may have overestimated food NF of seafood by using the simple assumption that aquacultured seafood is similar to livestock and that food production NF for captured seafood is negligible. In addition, the considerable size of NF for non-fed aquacultured and captured seafood (Figure 3.4) indicates the need to take account of non-fed seafood when assessing seafood. Similar to legumes on the land, even shellfish and mollusks, which are non-fed aquacultured or captured, have some positive food NF. Furthermore, the significant differences in NF among the seven categories of seafood (Figure 3.4) point to the need for a detailed consumption-based assessment tool for seafood, especially for consumers of large amounts of seafood. In this section, we first discuss important aspects of assessing the N_r load of seafood. Next we explore sustainable food choices, and then consider the reliability of the new NF model.

3.5.1 Approach for Assessing Seafood

Seafood production involves many species categories and uses a number of production systems ranging from captured fish or non-fed aquacultured shellfish to intensive shrimp farming. This differs largely from meat production, of which wild meat is not a realistic choice in most of the cases. Presenting only the average evaluation of a variety of seafood as in the existing NF model (Leach *et al*., 2012) does not provide information for consumers and suppliers to lower the environmental load of seafood when making their choices. In order to improve accuracy of assessing N_r load of seafood, in contrast to the case of livestock, we need to consider the fed aquaculture ratio and the plant protein ratio in feed (Table 3.5). The large differences in NF of seafood for changes of fed aquaculture ratio are primarily due to the recycling ratio at aquaculture farms (γ_3 and $\gamma_{3'}$ in Table 3.4). We considered the recycling ratios to be 0% from the fact that ordinary aquaculture farms do not recycle N_r from bottom sediment, in contrast to the common model which assumes the ratio to be 35%. Given the increasing trends of the fed-aquacultured ratio (FAO, 2012b) and the plant protein ratio in feed (Tacon *et al*., 2011), competition between the aquaculture sector and the livestock sector on the use of fishmeal and plant protein is likely to occur. Having an NF model sensitive to those ratios and the efforts to reduce the estimated NFs can lead N_r-effective fed aquaculture.

Consistent with this study, LCAs of aquacultured seafood (Aubin *et al*., 2009; Pelletier *et al*., 2009) have shown that feed composition and management are the dominant factors in N_r load. On the other hand, LCAs of captured seafood (Farmery *et al*., 2014; Pelletier *et al*., 2007; Ziegler *et al*., 2003) have also shown that N_r release at processing and sewage treatment steps, on which this study is focused, is much less than that of energy use in fisheries and transportation, which is not included in this study. Since the dominant factor differs according to feeding needs, it is important to evaluate N_r load separately for fed aquacultured seafood and non-fed seafood (aquacultured or captured seafood) before integrating them into one category. Further work is required to incorporate N_r release from energy use in addition to that related to seafood itself to calculate entire NF of captured, non-fed aquacultured and fed aquacultured seafood.

Several ecological footprint studies (Bunting, 2001; Folke *et al*., 1998; Kautsky *et al*., 1997; Robertson and Phillips, 1995) also focused on the N_r load of aquacultured seafood as additional ecosystem areas required for waste assimilation from aquaculture farms. However, the area required for assimilation varies in specific ecosystems, reflecting dynamic ecological pathways rather than area-related measures (Roth *et al*., 2000). In addition, in the process of integrating environmental loads of different resource uses, recent studies (Borucke *et al*., 2013; Parker and Tyedmers, 2012; Swartz *et al*., 2010; Talberth *et al*., 2006; Venetoulis and Talberth, 2007) have shifted the focus for seafood to the primary production required to sustain a harvested seafood species. The water footprint calculation (Gephart *et al*., 2014) even considered the water footprint of marine seafood to be zero despite its N_r load.

Other specific issues for seafood to be integrated in to the consideration of environmental loads include, for capture fisheries, the impact on stocks of the target and by-catch species, seafloor impact, and discarding (Ziegler *et al*., 2003); and for fed aquaculture, the use of antibiotics and aquatic medicines (Samuel-Fitwi *et al*., 2012). Although our results show that the average NF of seafood is much smaller than that of livestock meat, major issues for each production system differ. Captured seafood has low food NF but its major problem is overfishing. Sustainable fisheries including choosing species that have enough stock should be applied to reduce the overall environmental load. Fed aquaculture has higher food NF than pork and poultry meat together with other environmental impacts (Troell *et al*., 2014) so that more efforts are needed to improve the N_r-effectiveness. Non-fed aquaculture has low food NF and has no major issues. NFs of seafood produced by the three production systems should be calculated separately to tackle their environmental issues. If the world average seafood protein N consumption increase by 2.9 times from 2009 to 2022 with the increase of the fed aquaculture ratio from 10% to 28% (calculated from OECD/FAO (2013) and FAO (2014b), food NF of seafood will increase by 3.3 times (using parameter set W with the assumption of no changes in the species consumed). Therefore, our work on NF considering feeding is a necessary step toward a comprehensive assessment of seafood for sustainability with more integrated indices.

3.5.2 Nitrogen Footprint for Sustainable Food Choices in Seafood-Eating Countries

Aquaculture production is increasing in the world (e.g. by 7.5% from 2009 to 2010), and is vulnerable to adverse impacts of environmental conditions (FAO, 2012b). Moreover, it is pointed that integrated planning and management of aquaculture and fisheries is vital to their future sustainability (FAO, 2012b). Nitrogen loads from two kinds of seafood differ greatly and are important aspects of such integration and further integration to agriculture so that should not be grouped into a single category at the average evaluation of the two.

The virtual N factor (per intake N_r release during production) differs greatly between categories of food (Leach *et al*., 2012) and, with our model, even within categories of fed aquacultured seafood (Table 3.7 and Figure 3.5). The large NF for fed aquacultured crustaceans shown in this study is in line with the potential N_r load estimated by Boyd *et al*. (2007) for shrimp and some fed-aquacultured fishes. The weighted average virtual N factor of seafood was substantially lower with our model calculation than that in the common model; while the virtual N factor of fed aquacultured seafood remained relatively stable (Table 3.7). The reason for this is that non-fed seafood with substantially lower virtual N factors accounts for around 90% of protein intake, with both ratios for the world average and for Japan.

The comparison of our results with Shibata *et al*. (2014) who considered the ratios of aquaculture and self-sufficiency for Japan with the change of the VNF (Figures 3.3 and 3.5) indicates that modification of the model based on the three flows for each production system for each seafood category has more influence than change of the parameters.

In our model the virtual N factors with the two sets of parameters differed slightly from each other because of differences in plant protein feed and fed aquaculture ratios, as we estimated the same values for ratios of previous N_r available and N_r recycled due to data limitations. We could assume that application of the parameter set W to countries other than Japan with similar food systems would provide approximate estimations of food NF of seafood that are more accurate than those of the common model because of the small differences between the two sets of parameters. In addition, due to data limitations, in the N_r flows in Figure 3.1, we assumed an unknown proportion of recycled N_r from non-fed seafood offal goes back to the previous processes of any categories of seafood and the remainder, together with offal from fed aquacultured seafood, goes to other uses. Our overall results of 61% of offal fishmeal used as aquaculture feed is in line with the fact that 68.4% of all fishmeal produced (including whole fish fishmeal used for other purposes) is used as aquaculture feed (Tacon *et al*., 2011). Despite these limitations, our results suggest that eating more non-fed fish and less fed-aquacultured crustaceans, namely shrimps and prawns, could effectively reduce our food NF of seafood.

To provide indices for reducing the environmental impact from food choices, previous studies on carbon footprint (Pathak *et al*., 2010; Weber and Matthews, 2008) and N_r load (Leach *et al*., 2012; Xue and Landis, 2010) regarded fish as one category. Some other footprint studies of western diets even excluded fish from analysis (Chatzimpiros *et al*., 2013; Eshel *et al*., 2014; Leip *et al*., 2014). The standard version of the ecological footprint (Borucke *et al*., 2013) does not present detailed information on species, although Talberth *et al*. (2006) provided information for commonly eaten species. It is convenient to consider seafood as one category for understanding the general situation of the environmental load caused by global food consumption. However, according to the FAO (2014d), seafood contributed an average of 15% of all supplied food animal protein for the world. Moreover, the ratio differs greatly from country to country: it was 56% in Bangladesh, 55% in Indonesia, 43% in Nigeria and Myanmar, 38% in Japan, 35% in Thailand, 23% in Norway, 21% in China, 20% in Spain, and 7% in the USA and Germany in the year 2011 (FAO, 2014d). Other differences between countries include the ratio of fed-aquacultured seafood over total seafood consumption in each category. Therefore, indicators showing the difference between dishes with grilled captured fish, such as Pacific saury (*Cololabis saira*), and smoked fed-aquacultured fish, such as Atlantic salmon (*Salmo salar*), are better for putting information to practical use and, especially, for assessing regions with high seafood consumption and a variety of seafood choices. In Japan, for example, the food consumption pattern of modern Japanese has changed during the latter half of 20th century from the traditional Japanese pattern. The pattern shifted toward that of east coast Mediterranean Sea countries in 1960s, to that of major Europe and American countries in 1970s and 1980s, and to that of Latin American countries at the end of 20th century. (Yanagimoto, 2004). The transition has brought Japanese consumers a wide variety of choices in seafood to eat, along with the opportunity to eat beef, chicken, or other types of meat. We should also consider the trade-offs between the reduction of seafood consumption and the consequent increase of other protein consumption. Furthermore, depending on food cultures, production systems and their transitions in each region, there may be better models that treat other specific aspects of seafood production or species groups in detail.

3.5.3 Cross-check with Reactive Nitrogen Flow and Quality of Data

It is difficult to make a direct comparison with previous studies of food-related N_r flow in Japan (Miwa *et al*., 2006; Oda, 2006; Shindo *et al*., 2009), because they did not show seafood in detail but aggregated it to the total food production and consumption. However, where it is comparable, our estimates agree well with the flow estimated by Oda (2006) if the fish consumption in Japan declined by 22% from his studied year of 1997 to our studied year of 2009. We estimate, from the 1,220 g-N in per capita supplied seafood protein, about 155 Gg (1 Gg = 1,000 metric tons) of N was supplied to Japan in 2009, which is 3% larger than 150 Gg-N, calculated and adjusted from the estimation for 1997 by Oda (2006). For N_r applied as feed for seafood, our model with parameter set J estimates about 60.1 Gg-N, and which is 3% larger than 58.4 Gg-N adjusted from the amount in 1997 estimated by Oda (2006). Therefore, our estimation of ratios of feed N_r efficiency ($\alpha_{3'}$ in Table 3.4) can be used to quantify NF of seafood in a specific country. They are representative values for finfish and crustaceans.

The limitations of this study include the rough estimation of the fed aquaculture ratios in Table 3.5 and the ratios related to food waste, α_6 in Table 3.2 and γ_6 in Table 3. The fed aquaculture ratio was estimated from the ratio of fed aquacultured seafood to the total seafood, including seafood used for aquaculture feed. Seed production of fish was excluded from fed aquacultured seafood in the calculation due to the small feed consumption of fry. According to the FAO year book, fish for non-food use amounted to 21.8 Tg (1 Tg = 1 million metric tons) and captured fish amounted to 89.6 Tg in 2009 (Statistics and Information Branch of the Fisheries and Aquaculture Department, 2014). If we assume all of the non-food use seafood is used for aquaculture feed and is derived from captured seafood, then the seafood used for aquaculture feed can be estimated to be 24.3% of total captured seafood (21.8/89.6=24.3%). With this assumption, the weighted average of Japan's fed aquaculture ratio for all categories with parameter set W would change from 17.1% (weighted average calculated from supplied N_r (Section 3.4) and fed aquaculture ratio (Table 3.5) of each category) to 22.6% (17.1/(100 − 24.3) = 22.6%).This change of fed aquaculture ratio would increase Japan's NF of seafood to 1.70 kg-N/capita/year, which suggests Japan's NF of seafood was possibly underestimated in our model by a maximum of 10.2%.

The ratios related to seafood waste in this study were assumed to be 84% for food consumed (not wasted by consumers) and 0% for recycling ratios (α_6 in Table 3.2

and γ_6 in Table 3), which are the same as those of Leach *et al*. (2012). These assumptions are deduced from the fact that ordinary households do not make special efforts to reduce N_r waste nor to recycle N_r. For the ratio of seafood consumed, Oda and Matsumoto (2006) estimated a similar value of 86.21% for Japan. It is desirable for the ratio to be investigated together with the removal ratio (β) to maintain calculation accuracy when assessing different regions, because these ratios vary greatly between regions (Grizzetti *et al*., 2013) and also change reflecting transitions of customs in each region. For the recycling ratio, although food services give the ratio of 11% on the basis of weight (Ministry of Agriculture, Forestry and Fisheries of Japan, 2011), food waste from food services accounts for only 21% of the total food waste together with that from household (Ministry of Agriculture, Forestry and Fisheries of Japan, 2013) and the weighted average of the rate recycling ratio in total food waste is 3%. Even if we assume the recycling ratio to be 3%, NF of seafood with parameter set W decreases by less than 1%.

3.6 Conclusions

An NF model based on a seafood-specific approach can be used to provide practical information for consumers, policy makers and suppliers in CSR perspectives on the N_r load of different types of seafood in addition to other food items. It is essential for the approach to focus on the feeding step for the N_r load quantification because feed management in aquaculture has a much larger variety of choices than that of livestock. Surprisingly, fed aquacultured seafood accounted for less than half of Japanese NF of seafood; non-fed seafood which forms the majority of consumption has a larger N_r load despite its lower intensity. One remaining question is whether non-fed aquacultured seafood remains the best choice for sustainability among different types of seafood after integrating the N_r load in energy use and other seafood-specific issues.

NF models have recently been developed to raise awareness of N_r-related issues in food and energy with a common unit of quantification focusing on meat and dairy products. Our results demonstrate for the first time that our choice of whether to eat fed-aquacultured shrimps and prawns or captured fish and squids has a larger effect on N_r-related impacts than the choice between beef and poultry. With that information, ecologically conscious consumers can have a choice of eating seafood of lower-NF categories and production sources in addition to lower seafood/animal protein intake. In an effort to lower NF of seafood using our model, we can improve N_r use efficiency in both aquaculture production system and fisheries system at supplier level as well as primary producer level. The effectiveness of policies linking Aichi Biodiversity Target 4 (sustainable consumption), Target 6 (sustainable fisheries), Target 7 (sustainable aquaculture and agriculture) and Target 8 (pollution including excess nutrient) such as encouraging consumers to eat a variety of locally-grown wild fish, e.g. low-value fishes that are otherwise used as feed or wasted, instead of N_r-emission intensive food, can also be quantified with our NF model.

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Chater 4: Reduction Strategies for Nitrogen Emissions

4.1 Chapter Overview

The aims of this dissertation were: (1) to develop a novel global nitrogen footprint (NF) model for all nations; (2) to explore the global picture of the NFs and the role of international trade on it; (3) to develop an improved NF model for calculating NF of seafood production and consumption; (4) to provide more comprehensive and detailed information on food choices for reducing reactive nitrogen (Nr) emissions.

These aims were addressed by conducting literature and database surveys, providing Nr emission satellite-accounts data for and conducting extended input–output analysis based on the top-down global NF model, constructing more realistic flows for the calculation for the NF of seafood (including finfishes, crustaceans and mollusks, both inland and marine), and examining the parameters and virtual nitrogen factors (VNFs) of the bottom-up NF model. This provided preliminary information on the use of NF analysis for understanding a plant and seafood-based diet approach to reduce Nr within a global context.

The introductory chapter of this dissertation proposed four hypotheses regarding research conducted in the subsequent chapters:

(the global NF analysis)

1. Developed countries pollute agricultural countries through their consumption;
2. Agricultural and energy-intensive products are globally the key commodities for NFs;

(the investigation on NF of seafood)

3. Calculating NF of seafood requires a different approach from the approach for livestock;
4. Different types of seafood have diverse NFs per unit of protein.

The work presented in this dissertation provided support for these hypotheses. The first section of this concluding chapter summarizes and discusses the main findings of each chapter and conducts further discussions on the methodologies. The second section of this chapter explores an effective way to reduce Nr emissions through dietary choices. The third section of this chapter explores a role of NF analysis for further integration of environmental impact assessments to provide better strategies to address various environmental impacts.

4.2 Summary of Findings and Additional Discussion

4.2.1 Chapter 2. Substantial nitrogen pollution embedded in international trade

Chapter 2 described the role of international trade on the global NF as an important driver of wealthy nations' high NFs. Top ten nations of territorial-based emissions were reported to bear 59% of the global Nr emissions (China 20.3%, India 11.1%, the United States of America (USA) 9.7%, Brazil 6.1%, Russia 2.2%, Indonesia 2.2%, Pakistan 2.1%, Australia 1.7%, Mexico 1.7% and Argentina 1.5%). Of the ten countries, Pakistan, Australia and Argentina are not in the top ten nations of NF contributing to 59% of the global Nr emissions through their consumption (China 19.4%, India 10.6%, USA 10.2%, Brazil 6.0%, Japan 2.7%, Russia 2.5%, Indonesia 2.3%, Germany 1.9%, Mexico 1.9% and the United Kingdom (UK) 1.8%). International trade enables Japan, Germany and the UK to be in the top ten consumption-based Nr emitters. Through importing high-Nr-emissions-embedded commodities including clothing as well as agricultural food from resource-rich countries (often developing countries), developed countries are polluting environment of the producing countries. The resources rich in those countries vary from crops (both for direct human use and for feed) and livestock production to manufacturing industries (especially for textiles, clothing, leather goods and footwear) and petroleum and natural gas industries. On per-capita basis, the analysis showed that not only the countries with a high meat diet (Galloway *et al.*, 2014; Leach *et al.*, 2012), but also the countries with high per-capita GDPs and high dependence on products that have long supply chains.

Methodological Advantages and Limitations

The default method (Tier 1) by Intergovernmental Panel on Climate Change (IPCC, 2006) is used in Chapter 2 to calculate the Nr emissions from production data, fertilizer data, and data for emissions from manure. The Tier 1 method is useful to estimate emissions from countries with limited data and to gain the global picture of the Nr emissions, being sensitive to the input of production systems. In addition, the calculated relative standard deviations for the total Nr emissions (Section 2.3.5) of the 20 countries on Figure 2.4 are 16% in average and mostly below 25% with exception for Pakistan (47%) and Mongolia (29%). However, providing more detailed information, e.g. differentiate good practice on soil and manure management, grass-fed cattle from grain-fed cattle, differentiate different types of fisheries etc., would help consumers who are willing to reduce their NFs by choosing the products with lower NFs. Incorporating those points first to the country-specific model for individuals (the N-Calculator; N-Print, 2011) is easier to overcome the data limitations. Thus, the bottom-up approach to calculate NFs of different types of seafood is used in Chapter 3.

An extended multi-region input–output (MRIO) analysis was performed in Chapter 2 to link hotspots of nitrogen pollution to centres of consumption. MRIO analysis is a powerful tool to trace the international supply chains and has the advantage of comprehensiveness, defining system boundaries as absolute (Feng *et al*., 2011), fully considering re-exports and avoiding double counting (Bruckner *et al*., 2015). However, since agricultural sectors are aggregated to one or a few sectors in many countries, this method with homogeneity assumption for each sector is affected by aggregation errors (Table 2.2). In those cases, the agricultural sectors for each country including both cash crops and livestock for domestic use have NFs mainly from livestock but methodologically, export NFs embodied in cash crops are in proportion to their monetary values. With the proportionally assumption (value-to-weight ratio) of MRIO analysis, the countries and entities with high per-capita GDPs, such as Hong Kong, which are possibly importing mainly higher quality products with higher monetary values in the sectors of trading partners, might have higher calculated NFs than actually embodied NFs. Although the above issues can be avoided by using physical flows for the analysis, structural path analysis to trace the supply chains cannot be applied in physical accounting. In addition, chains of highly manufactured biotic products, in particular those of non-food products such as textiles cannot be modelled on the basis of available agricultural statistics alone (Bruckner *et al*., 2015). Therefore, the findings of textiles and leathers being as key commodities and their representative paths starting from China, India and Mali to the USA, Japan, Germany and Korea (Table 2.5) are, for example, specific contributions of MRIO approach.

To track all embodied high flows in a top-down system from primary production to final consumption more accurately in future studies, hybrid methods for combining physical accounting and MRIO analysis should be investigated as suggested for ecological footprint (EF) and water footprint (WF) (Ewing *et al*., 2012) and land footprint (Bruckner *et al*., 2015) with careful consideration on the frameworks to avoid double counting (Lenzen, 2009, 2008b; Strømman *et al*., 2009; Suh, 2004). Those hybrid methods can potentially be integrated into a global mixed-unit input–output model (Bruckner and Moran, 2015), which would provide a high level of transparency and reproducibility and allow using structural path analysis (Bruckner *et al*., 2015).

Comparison to Other Footprint Studies

The top ten nations' share of 59% of the global NF exhibits a more distributed pattern compared to 73% for carbon footprint (CF; Hertwich and Peters, 2009) and similar to ca. 59% for EF (WWF, 2014). The top ten nations for NF, CF, and EF are almost the same because of their high-energy and high-nutrient life and/or no denitrification at waste water treatment plant, in addition to their large population.

The polluter-recipient trend shown in Chapter 2 in line with that found for greenhouse gas (GHG) emissions (Kanemoto *et al*., 2014; Peters *et al*., 2012), scarce water (Lenzen *et al*., 2013a), land use (Weinzettel *et al*., 2013) and natural resources (Wiedmann *et al*., 2015) with Japan, the European Union countries, and the USA being on the polluter/user side where as China, India, Pakistan, Brazil and Australia being on the recipient /provider side. Russia is on the polluter/user side in our nitrogen analysis, the analyses on scares water and natural resources but on the recipient/provider side in the analyses on GHG emissions and land use, reflecting their large ores and minerals industry, including petroleum and gas extraction.

The result of the USA being on the polluter/user side differs from Lassaletta *et al*. (2014a) who used physical accounting and did not consider processing for their nitrogen calculation. The reason is that even larger nitrogen emissions embodied in import of the USA cancels out those in their large export. China also comes to the polluter/user side for GHG emissions in another physical accounting study by Kastner *et al*. (2011), considering multiple levels of trade but not processing. Since there is considerable processing of raw materials in China before being exported as manufactured product, different levels of processing should be a cause of the differences in the results for China (Gu *et al*., 2012; Peters *et al*., 2012) and its primary recipient, the USA. Further investigation is required to fully understand the differences between the methods used shown here and in Peters *et al*. (2012).

The relatively lower per-capita NFs for ammonia (NH_3) and nitrogen exportable to water bodies (Nwp) for Japan among developed nations shown in Chapter 2 do not in line with the higher per-capita food NF compared to Europe reported by Shibata *et al*. (2014) using the bottom-up approach of N-calculator. However, their analysis with a partial consideration of international trading calculates the per-capita total NF for Japan lower than their calculation without international trade. Given the high importing rate for Japanese food consumption, this trend indicates that the per-capita total NF for Japan would become lower when we fully consider Japan's international trading.

Implications to Global Nitrogen Reduction Strategies

On per-capita basis, Chapter 2 showed that NFs range greatly from under 7 kg N yr^{-1} to over 100 kg N yr^{-1}. Given the planetary boundary of human Nr introduction (agricultural nitrogen fixation) of 62–82 Tg N yr^{-1} (de Vries *et al.*, 2013; Steffen *et al.*, 2015), or 8.3–10.9 kg N cap^{-1} yr^{-1} (assuming the world population of 7.5 billion), only 3.3–7.2%, or 250–540 million people, are living in the state below this boundary (assuming all Nr introduction is to supply the Nr lossed to the environment as food NF). Facing the threads of excess Nr on water quality, air quality, greenhouse balance, ecosystems and biodiversity, and soil quality (Sutton *et al.*, 2011), there is an urgent need to make the whole world more sustainable.

The key international commodity flows of embodied Nr emissions between countries are shown in Chapter 2 (Figure 2.6 and Tables 2.3–2.4); from China to the USA and to Japan, from the USA to Japan, from India to the USA, among European countries, and among the USA, Canada, and Mexico. While the NFs can be decomposed into two ways (Appendix 1.1.1), the chapter is more focused on the consumption perspective (Figure 2.6 and Tables 2.4 and 2.5; flows between countries of final sale to countries of final consumption) than the production perspective (Figures 2.4 and 2.5; countries of production to countries of final consumption) to address the issue from the consumer side. The flows indicate that particular attention should be given to these trade routes to reduce the global Nr emissions, for example, by introducing certification (e.g. Aquaculture Stewardship Council, ASC), product labelling on the high-NF products and surcharge for the high-NF embedded on the product.

Clothing (textiles and leathers) and other energy-intensive goods and services (including transport) as well as meat are found to be the key commodities for high per-capita NFs. Many developed countries have net-import of NF for nitrogen oxide (NO_x) for their imports of processed products from China, because China has coal-dominated electricity production and manufacturing and transportation with diesel and gasoline engines (Shi *et al.*, 2014). To achieve nitrogen oxides (NO_x) emissions reduction in China, it is urgently required to improve energy efficiency, install more renewable power, and strengthen supervision on energy-intensive industries. Since one-third of CO_2 emissions in China were due to production of exports in 2005 with the rise from 21% in 2002 (Weber *et al.*, 2008), those developed countries as well as China itself are responsible for the 2.1 times increase of NO_x emissions from 2000 to 2010, suggesting technology transfer should be encouraged.

Countries with large area that have high per-capita NFs for NO_x are the USA (Chapter 2; Galloway *et al*., 2014; Leach *et al*., 2012) and Australia (Chapter 2). Improving access to the affordable and convenient public transportation systems and introducing more environmentally-transport system to provide low-nitrogen-embedded as well as low-carbon embedded (Korkala *et al*., 2014) options are particularly important in those countries.

Asian countries and entities including Japan and South Korea, but excluding Hong Kong, were shown to have relatively low per-capita NFs for NH_3 and Nwp (Chapter 2), because of their diets with less meat (FAO, 2015). The analysis confirmed that, in order to lower per-capita NF and subsequent Nr emissions in both local and distant regions, globally, food choices have substantial impacts (Leach *et al*., 2012) as well as the preference on non-food animal products, natural textiles and other agricultural products. Further investigation is needed for accurately calculating different diets with different production systems in each region to help consumers lower their NFs. It should also be noted for future studies that the people affected by nitrogen pollution in developed countries are likely to be low-income minorities (e.g. the case of the USA shown in Chapter 2; Balazs *et al*., 2011), and dietary patterns varies by income even within a nation (e.g. Xie *et al*., 2003). For better understanding a plant and seafood-based diet, often seen in Asia, we focused on seafood in Chapter 3.

4.2.2 Chapter 3. An improved methodology for calculating the nitrogen footprint of seafood

Chapter 3 reported that, unlike the calculation for livestock, calculating NF of seafood should consider three kinds of production systems (for fed aquaculture, non-fed aquaculture and capture fisheries), requiring a different approach from the existing approach for livestock. Since captured seafood is used directly as human food and indirectly as feed for aquacultured seafood, designing a set of flows linked each other for the three kinds of production systems is more realistic for calculating NF of seafood. Producing aquacultured seafood uses both crops and captured fish or its products. Due to the fertilizer assumed to be used to grow the crops, crop-eating aquacultured seafood has higher NF than fish-eating aquacultured seafood. Thus, fed-aquacultured shrimps and prawns were found to have about ten times more NF than that of captured seafood. Since captured seafood is the main source of Japanese seafood consumption, when calculated the three kinds of seafood production system separately, the seafood NF for Japan was found to be less than half of that calculated by the previous model using the parameters for the USA (Leach *et al*., 2012) and roughly 50-60% when using adjusted parameters for Japan (Leach *et al*., 2012; Shibata *et al*., 2014).

Methodological Advantages and Limitations

The bottom-up approach taken in Chapter 3, the N-calculator approach for the food NF component, is used to link what people actually eat and Nr emissions. This approach can be used as a tool for individual consumers to understand the nitrogen issues in relation with their consumption and to find ways to reduce their NFs (Leach *et al*., 2012). The advantages of the approach are simplicity for understanding, directness to provide information on the final commodities consumed (Leach *et al*., 2012), considering physical flows in production systems for a target country, and sensitivity to detailed food choices (Shibata *et al*., 2014; Stevens *et al*., 2014). However, this method lucks the capability to show in detail where and what kind of the impacts are induced through the consumption in addition to the inter-sectoral cut-offs and inter-regional cut-offs (Feng *et al.*, 2011). Besides, the results are affected by dissimilarity of the production systems for internationally-traded commodities. While the MRIO approach in Chapter 2 can be used as complement for the country-level NF in total, the results are neither detailed in sectors to differentiate aquaculture and fisheries nor consider the Nwp emitted at aquaculture farms and other industries except agriculture. The results in Chapter 3 indicate that the Nr emissions (mainly Nwp and NH_3) induced by Japanese food consumption, are generated mostly in shrimp farms in Asian countries, salmon and trout farms in Chile and Norway, and in agricultural farms where the plant-based food used in those countries comes from. The inter-sectoral cut-offs and inter-regional cut-offs are assumed to be minor as food is Nr-intensive commodities, similar to the energy-intensive commodities (Lenzen, 2008a). The errors arising from dissimilarity can be substantially addressed by considering the main trading countries (Chapter 3; Shibata *et al*., 2014).

Implications to Reduce Food Nitrogen Footprint

Chapter 3 showed that even applying the common model for livestock and seafood, Japanese diet with less meat and more seafood has an NF of 17.2 kg N cap^{-1} yr^{-1} for the total food NF (3.71 + 13.46), which is lower than the US-American diet of 23.7 kg N cap^{-1} yr^{-1} and the Dutch diet of 21.6 kg N cap^{-1} yr^{-1} (calculated from Galloway *et al*., 2014 with adjustment of denitrification for sewage treatment to 32% as calculated for Japan). Since captured and non-fed aquacultured seafood is the main source of Japanese seafood consumption, when calculated the three kinds of seafood production system separately, the Japanese total food NF is further lower (15.01 kg N cap^{-1} yr^{-1} with parameter set J). Similarly, in many parts of Asia, where artisanal fishing are vital to livelihood (FAO, 2014) , NF of seafood is assumed to be equal to that of captured seafood, leading to low food NF for their diets based on plant and seafood.

In the analysis of Chapter 3, feed composition and management are shown to be the dominant factors for NF of fed aquacultured seafood. Although NF of each product differs in detail, these results indicate that consumers can reduce their NFs by shifting grain-fed beef consumption to captured seafood or non-fed aquacultured seafood as well as to poultry and other meat. In the current situation, this alternative option would change the place of emissions generation for Japanese food NF from Australia and the USA, where much of beef comes from, to Japan, China, South Korea, and Russia, where captured seafood and non-fed aquacultured seafood comes from. To help consumers making wider choices, certifications and product labelling for NF of products should focus on shrimp farms and salmon farms in order to shift their nitrogen use efficiency (NUE) higher. Since the analysis is focused only on NF, other aspects should also be considered to examine some options for a more sustainable diet (e.g. GHG emissions of different food types shown in Tilman and Clark, 2014). The relationship between diet and NF is analysed for the case of Japan in the next section.

4.3 Strategies in Food Choice: A Case Study in Japan

4.3.1 Background Information

Diets tightly link human health and environmental problems (Tilman and Clark, 2014)., including nitrogen pollution. Stevens *et al.*, (2014) reported that food has a larger impact than energy in their scenario analysis and presented that the scenario of protein consumption lowering to the level recommended by the World Health Organization (WHO) and United States Department of Agriculture (USDA) slashes the NF for the UK most significantly among the scenarios tested. Some studies have shown that a traditional Japanese diet provides health benefits, such as reducing risks of cardiovascular disease and diabetes (Guo *et al.*, 2012; Shimazu *et al.*, 2007) and enhancing life expectancy and delaying senescence (Yamamoto *et al.*, 2015). The traditional Japanese diet is characterized by a high consumption of soybean products, fish, seaweeds, vegetables, fruits and green tea (Shimazu *et al*., 2007). Since the Japanese diet has shifted toward an animal-protein-rich diet, similar to the American diet over the past 50 years, the 1975 diet has been reported to offer more health benefits than the current diet (Yamamoto *et al*., 2015). However, our food choices are made not only depending on how environment-friendly and healthy the food is, but also on culture, nutritional knowledge, price, availability, taste and convenience (Tilman and Clark, 2014). To examine some potential dietary solutions to address this diet–environment–health trilemma, impact of dietary changes on the food NF in Japan is assessed in the following subsections.

4.3.2 Methods

The per capita food NF is defined as "the total amount of Nr released to the environment as a result of an average individual's food consumption, except any energy-related nitrogen" (Leach *et al*., 2012). The food NF is composed of two parts: food production and food consumption. Food production NF is determined as nitrogen consumption multiplied by VNFs, which indicates the amount of Nr released to the environment during production per unit of nitrogen consumed. Food consumption NF is the nitrogen consumption subtracted by the average rate of denitrification in sewage treatment.

Food NF for Japan was assessed using FAO food protein supply data for 1961–2011, or the maximum period available (FAO, 2015) and the VNFs, the average food waste rates and the fed-aquacultured rates for Japan shown in Table 4.1 (Chapter 3; Shibata *et al*., 2014), and the average rate of denitrification in sewage treatment of 32% (Oda and Matsumoto, 2006), following Leach *et al.* (2012). Supplied food protein is subtracted by the average food waste rates, yielding protein consumption. Protein consumption is multiplied by the nitrogen content of 16% to obtain nitrogen consumption. The term "meat" in this analysis includes offal as well as meat in the FAO categories.

Japanese NFs for four alternative dietary scenarios were compared based on the current average Japanese diet (the 2011 diet):

(1) *Recommended protein*: protein consumption is decreased to the level recommended by the Ministry of Health, Labour and Welfare of Japan (JMHLW), with the current dietary composition (Kido *et al*., 2012).

(2) *Pescetarian diet*: meat protein consumption is substituted by fish and seafood protein. Total protein consumption holds the current consumption level.

(3) *Low nitrogen footprint food diet*: protein consumption of meat, dairy, egg, and fed aquacultured, fish and seafood is substituted by legume protein, and captured and non-fed aquacultured, fish and seafood protein. Total protein consumption holds the current consumption level. Captured fish and seafood should be fished within biologically sustainable levels.

(4) *Balanced Japanese diet*: protein consumption is changed to the level consumed in 1975 with the dietary composition at that time.

Table 4.1 Virtual nitrogen factors (VNFs), food waste rates, and fed aquacultured rates for Japan.

Food category	VNFs[a]	Food waste rate[b] (%)	Fed aquacultured rate[c] (%)
Poultry meat	6.0	69	–
Pigmeat	6.7	61	–
Bovine meat	12.4	61	–
Milk and dairy products	2.7	97	–
Fish and seafood	–	84	–
Freshwater fish	–	–	58
Fed aquacultured	4.3	–	–
Captured and non-fed aquacultured	0.2	–	–
Marine fish[d]	–	–	5-6[e]
Fed aquacultured	3.4	–	–
Captured and non-fed aquacultured	0.2	–	–
Crustaceans	–	–	50
Fed aquacultured	7.6	–	–
Captured and non-fed aquacultured	0.2	–	–
Molluscs[f]	0.2	–	0
Cereals	1.5	90	–
Vegetables	5.5	80	–
Starchy roots	4.9	80	–
Legumes	1.3	91	–

[a] VNFs for the categories other than fish and seafood are VNFs for "Japan with trade" in Shibata *et al.* (2014) and VNFs for fish and seafood are VNFs for parameter set J in Chapter 3.

[b] Shibata *et al.* (2014).

[c] Parameter set J in Chapter 3.

[d] Marine fish includes FAO categories of demersal fish, pelagic fish and "marine fish, other".

[e] Marine fish includes FAO categories of cephalopods and "molluscs, other", both of which are considered not to be fed aquacultured.

[f] Marine fish includes FAO categories of cephalopods and "molluscs, other", both of which are considered not to be fed aquacultured.

4.3.3 Results

Protein Consumption

Between 1961 and 2011, the per capita protein consumption in Japan showed three trends: a steady increase from 1961 (64.6 g cap^{-1} day^{-1}) to 1989 (81.6 g cap^{-1} day^{-1}), followed by a slight decrease from 1989 to 2001 (79.8 g cap^{-1} day^{-1}); a moderate decrease from 2001 to 2011 (72.0 g cap^{-1} day^{-1}; Figure 4.1). The first period was the decades of a growth in food consumption, in particular, of meat (+360%), of dairy and egg (+183%), and of fish and seafood (+71%), with the exception of reduction in cereals (-25%) and legumes (-11%). In the second period, meat consumption kept the rise by 12%, but fish and seafood consumption started to lessen by 7%; the consumption of dairy and egg levelled off, and that of cereals and legumes continued to decline. During the third period, although meat consumption has remained to increase by 8%, fish and seafood consumption further shrank by 27%; the other categories' consumption has lowered slightly.

The relative proportion of each category to the total protein consumption has changed drastically over the 50 years (Figure 4.1 and Table 4.2). In 1961, cereals and legumes supplied over 60% of the total protein consumption, and fish and seafood was the main source of animal protein. By 1975, the percentage of cereals and legumes dropped to around 50% of the total protein consumption; of the animal protein consumption, dairy and egg added 25% and meat added 17% becoming the complement to fish and seafood. In 1989 and 2001, cereals and legumes shared only around 40% of the total protein consumption, and meat, dairy and egg increased to comprise a quarter of the total, leading the animal protein's share of more than 50% of the total. In 2011, while the contributions of vegetable products remain stable, that of meat, dairy and egg becomes nearly 60% of the animal protein consumption.

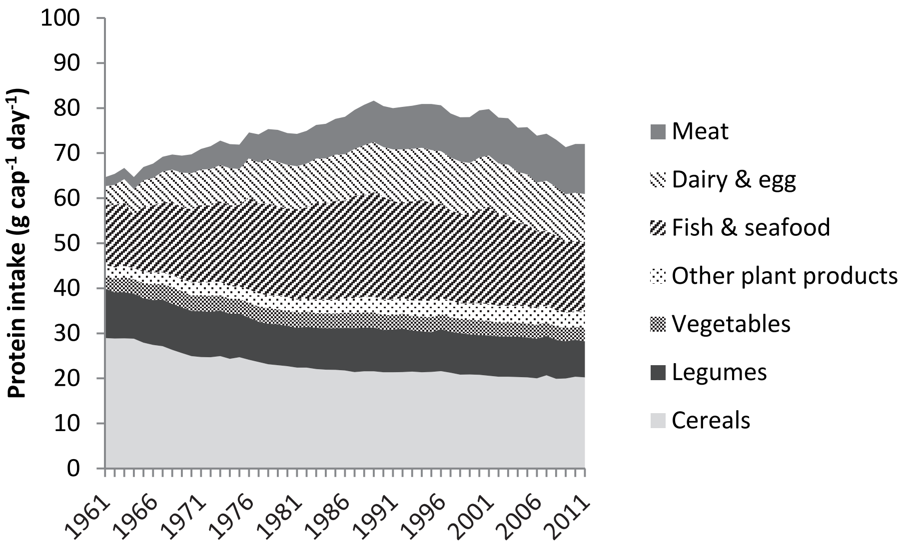

Figure 4.1 Protein consumption (g cap^{-1} day^{-1}) for major food groups between 1961 and 2011 in Japan (FAO, 2015)**.**

Table 4.2 Protein composition changes between 1961 and 2011 in Japan (g cap^{-1} day^{-1}).

Food category	1961		1975		1989		2001		2011	
Cereals	29.0	(45%)	24.7	(34%)	21.6	(26%)	20.6	(26%)	20.2	(28%)
Legumes	11.0	(17%)	9.7	(13%)	9.7	(12%)	9.0	(11%)	8.0	(11%)
Vegetables	2.7	(4%)	3.3	(5%)	3.4	(4%)	3.2	(4%)	3.0	(4%)
Other vegetable products	2.5	(4%)	2.7	(4%)	3.5	(4%)	3.7	(5%)	3.5	(5%)
Fish and seafood	13.6	(21%)	18.2	(25%)	23.2	(28%)	21.6	(27%)	15.7	(22%)
Dairy and egg	3.9	(6%)	7.9	(11%)	11.1	(14%)	11.4	(14%)	10.5	(15%)
Meat	2.0	(3%)	5.4	(8%)	9.2	(11%)	10.3	(13%)	11.1	(15%)
Total protein consumption	64.6	(100%)	71.9	(100%)	81.6	(100%)	79.8	(100%)	72.0	(100%)

The Per Capita Food Nitrogen Footprint

The per capita food NF in Japan was found to be 15.2 kg N yr^{-1} in 2011 with VNFs for Japan (Figure 4.2), as a sum of food production NF (12.3 kg N yr^{-1}) and food consumption NF (2.9 kg N yr^{-1}). Meat contributed 35% to the total food NF, followed by dairy and egg (19%), cereals (17%), and fish and seafood (9%). Calculated under the assumption of the constant VNFs for Japan, the NF increased from 1961 (9.8 kg N cap^{-1} yr^{-1}) to 1989 (15.7 kg N cap^{-1} yr^{-1}) with the growth in protein consumption, kept increasing with the continuous rise in meat consumption and reached a peak at 1995 (16.4 kg N cap^{-1} yr^{-1}); the NF levelled off until 2000, and thereafter slightly decreased to the current situation. Although protein consumption and the resultant food consumption NF in 2011 is only 11% greater compared with 1961, the total food NF is 60% greater.

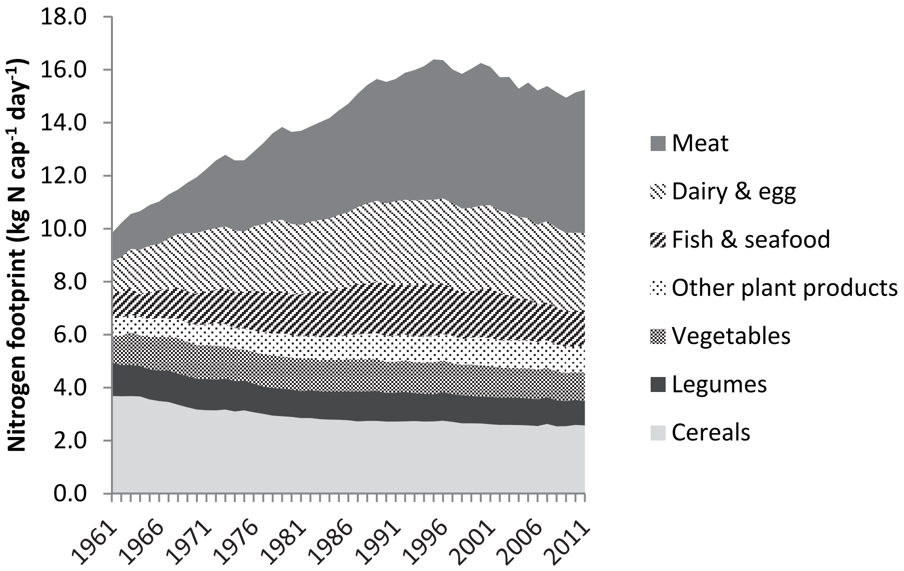

Figure 4.2 Impact of dietary changes between 1961 and 2011 on the food nitrogen footprint in Japan, calculated with the assumption of the constant virtual nitrogen factors (kg N cap^{-1} yr^{-1}).

Scenario Analysis

Dietary scenarios were used to access how individuals can contribute to reduce their food NF through changes in their food choices. To address the reduction, we could lower the amount of protein consumption and VNFs of the food we have. While diminishing food protein consumption to the JMHLW recommended level with the current dietary pattern decreases the NF by 26%, keeping the same protein consumption level with a Pescetarian diet (a diet without meat) lessens the NF by 29%. Consuming only low NF food while keeping the same protein consumption level is the most effective choice among the all scenarios tested, dropping the NF by 45%. In addition, the case of consuming a balanced Japanese diet as in 1975, which has roughly the same protein content, can also decline the NF by 17%.

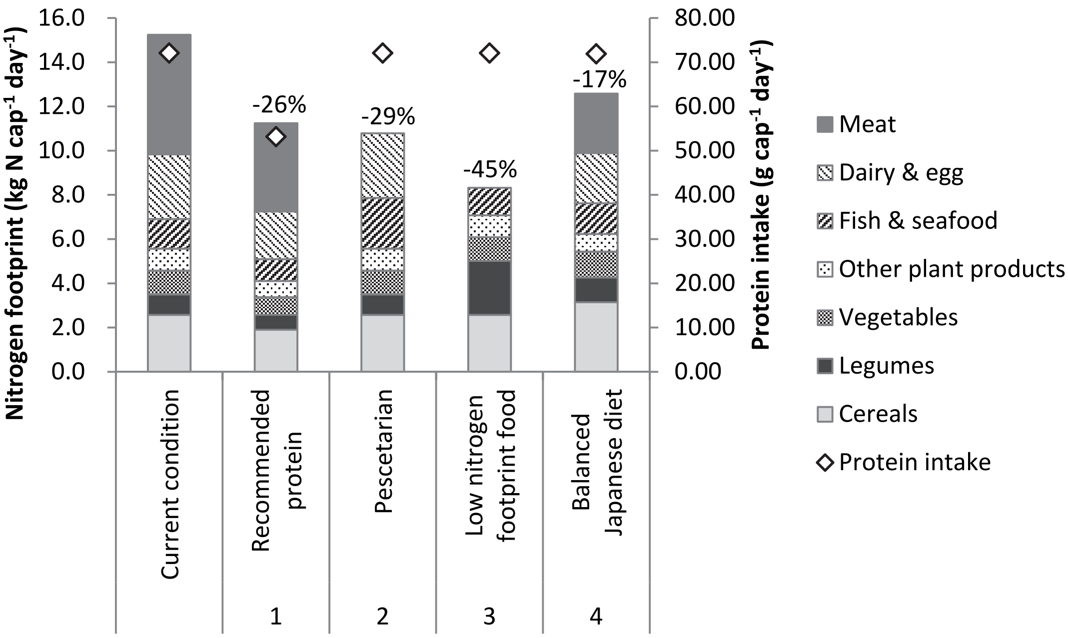

Figure 4.3 Food nitrogen footprints and total protein consumption for the scenarios decomposed into food categories. The scenarios analysed are: (1) cut protein consumption down to the level recommended by the Ministry of Health, Labour and Welfare of Japan (Kido *et al*., 2012); (2) consume more fish and seafood to replace protein consumption from meat; (3) consume more legumes and fish and seafood that is non-fed aquacultured or captured, to replace protein consumption of meat, dairy, egg, and fed aquacultured, fish and seafood; (4) consume a balanced Japanese diet as did in 1975**.**

4.3.4 Discussion

Dietary Changes and Food Nitrogen Footprint over the Past 50 Years

Overall, the per capita food NF in Japan has largely increased in the past five decades due to the growth in food consumption, especially in animal protein, in the first three decades and the shift to a more meat-based diet in the following two decades. Similar trends in these causes of environmental impacts can be seen in many of both developed and developing countries as ongoing changes (Alexandratos *et al*., 2006; Kearney, 2010). The increased consumption, especially in animal protein, has been supported by imported food and feed, resulting in the nitrogen pollution in the importing partners (Chapter 2; Burke *et al*., 2009) as well as the rise of nitrogen levels in water bodies in the imported countries (Lassaletta *et al*., 2014b; Shindo *et al*., 2009). Although the food NF in Japan is on a slight decline in the last decade, a larger reduction is required to shift to a sustainable diet within the planetary boundary (de Vries *et al.*, 2013; Steffen *et al.*, 2015) for keeping surface water below the level for aquatic ecosystems to develop eutrophication or acidification.

Choices of Alternative Diets

The dietary scenario analysis in Japan demonstrated that dietary pattern changes could achieve further reduction compared to lowering protein consumption to the JMHLW recommended level (53 g cap^{-1} day^{-1} for the average adult). Most of Japanese consume less than the upper limit of protein intake (118 g day^{-1}; Kido *et al.*, 2012) and some have insufficient protein intake (Mean±SD, 69.8 ± 23.2 g day^{-1}; JMHLW, 2013). In addition, some studies report that eldery people should take more protein than the recommended levels (Kobayashi *et al.*, 2013; Levine *et al.*, 2014). Therefore, changing dietary pattern is more favorable for many of Japanese to decrease their food NF.

Comparing the scenarios of the Pescetarian diet and the low NF food diet, a shift to a plant and seafood-based diet is 1.5 times more effective to reduce the food NF for Japan. From the dietary and supply perspective, the Pescetarian diet scenario is to consume 1.7 times more seafood than the current level and the low NF food diet scenario 1.6 times, which are 16% (Pescetarian) and 5% (low NF food) more than the level of the 1989 diet. The amount of consumption as the country level would be practicable to supply when wild stocks are sustainably managed at the degree of 1980s (MAFF, 2015a). The low NF food diet scenario is also set to consume 2.6 times more legumes than the current level, or 92% more than the 1961 diet. Still, Japan has a potential to produce 2.4 times more soybeans than the current level (MAFF, 2015b). This level of legume consumption is roughly the same as that of Niger in 2011 (FAO, 2015). Both senarios are on the diet that would be affordable, assuming the consumption increase mainly in wildly-caught small pelagic fish and legumes. Considering these situations, the Pescetarian diet appears to be a feasible option and the low NF diet has a potential to be taken by Japanese. In practice, these two diets could be taken once in a week, for example, as a day without meat, or a day without meat, dairy, egg, and fed aquacultured, fish and seafood.

From human health perspective, the option of balanced Japanese diet would be even more attractive, seeing the world longest life expectancy of Japanese women (WHO, 2014). To follow this diet is to consume less meat, dairy, and egg, and more rice and soybeans than the current diet. Although this option decreases smaller amount of NF compared to the other scenarios, it would be favorable for many consumers to carry out because this is the typical diet that most of people at that time had, and consumers do not need to cut any food categories. In conbination with a day in a week without meat, dairy, egg, and fed aquacultured, fish and seafood, we can reduce our NFs by more than 20%.

4.4 Integration of Footprints and Environmental Trade-offs

Recent discussion on development regards protecting the environment crucial for sustainability reflecting emerging issues on ecosystem services caused as adverse effects of human activities including impacts of excess Nr seen in Chapter 1 (e.g. nitrite contamination of drinking waterm, air pollution leading loss of some statistical life expectancy and of crop yield, and water pollution). The sustainable development goals (SDGs) are for all the nations and not just for poor and emerging nations that the Millennium Development Goals (MDGs) targeted at. Sustainable production and consumption is one of the key aspects (United Nations, 2015). In response from science community, an expanding list of environmental footprints has been developed (Čuček *et al.*, 2012a). Focusing exclusively on a single footprint carries the risk of shifting the environmental impact from one field to another (Fang *et al.*, 2014). Integrated system approach enables policy makers addressing multiple issues simultaneously and helps improving efficiency in actions in related sectors (Galli *et al.*, 2012). Comparisons of environmental footprints to the maximum sustainable level have also been proposed to contribute to prioritisation of the impacts of different fields (De Benedetto and Klemeš, 2009; Fang *et al.*, 2015; Hoekstra and Wiedmann, 2014).

MRIO approach has been introduced to NF in Chapter 2 for the first time. The global NF model enables future research to use NF as a part of an integrated top-down analysis with EF, WF, CF, material footprint etc. Since the global NF model differentiates each forms of Nr, it also allows us to see the trade-offs between different nitrogen species, for example, use of catalytic converters for vehicles to remove pollutants including NO_x from exhaust gases increases nitrous oxide (N_2O). The integrated top-down analysis can provide policy makers with quantitative information of trade-offs among the nitrogen issues and other issues. The energy and transportation sectors drive both NF and CF in use of fossil fuels. Increasing efficiency by combustion facility design and control is useful action to tackle both of the emissions. However, using biofuels increases NF and decreases CF compared to fossil fuels (Čuček *et al.*, 2012b). In addition, the most used feedstocks for the current first generation bio-fuel's production are corn, wheat, and sugarcane for bioethanol, and soybean, rapeseed and sunflower for biodiesel production. These feedstocks are also used for food and feed production. The use of NF in a set of indicators would also lead food-related sector more focused in strategic environmental policies, since it is the key sector for the nitrogen issues and not for the carbon issues.

On a smaller basis, Chapter 3 showed fed aquacultured crustaceans as the highest-NF seafood due to their low feed conversion rate and their higher dependence on vegetable protein that is assumed to be made from crops grown using nitrogen fertilizer. This could mean that we should use more captured fish for aquaculture to reduce NF of fed aquacultured seafood. Owing to the growing demand for fishmeal and fish oil and rising prices, more fishmeal is being produced from fish by-products, which previously were often discarded (FAO, 2014). At first glance, this seems to be good news, which can reduce NF and improve the resource usage rate. However, the use of by-products can affect the quality of the fishmeal to have more bone content, which is rich in calcium and phosphorus than conventional fishmeal (Naylor *et al*., 2009). That poor quality fishmeal could lead water pollution from aquaculture farms even more problematic and can cause zinc deficiency in freshwater aquacultured fish. To reduce NF of fed aquacultured fish and seafood in the efforts to lessen the overall environmental impacts, the important thing is that we improve NUE and other resource use efficiency in each step of production, especially in feed management (Boissy *et al*., 2011; Boyd *et al*., 2007). Since the NF model for seafood is sensitive to the efforts of increasing efficiency in aquaculture and other production steps at commodity level, it can be incorporated into an integrated assessment for seafood, providing quantitative information on nitrogen pollution along with other pollution, resource use, health of aquacultured seafood, and wild stocks of seafood.

As described above, although NF is not a single indicator that can comprehensively cover various environmental trade-offs, it can be used in a set of integrated indicators to provide quantitative information for policy makers, practitioners and consumers to see the trade-offs between different fields, leading strategic, inter-sectoral (e.g. food supply, human health and environment) policies and environmental actions to be more effective in addressing various issues including the nitrogen issues.

4.5 Conclusions

Anthropogenic Nr emissions are far beyond the sustainable limits. The excess Nr pollutes air, water and soil, threatening environment and human health. This study showed how NF can measure the environmental load of Nr for an individual level to the global level.

The global NF model analysis proved that agricultural food and clothing are globally the key commodities for NFs. The analysis demonstrated that the countries, often developing countries, with large capacity for the export of the key commodities are substantially polluted by demand of consumers in other countries, mainly developed countries, as well as their own. The global analysis suggested that per capita NFs tend to be lower in the Asian countries that have plant and seafood-based diets with less meat. The investigation on calculating food NF illustrated the need for a different methodology for seafood from the one for livestock. The new NF model for seafood revealed that NFs of seafood range from the load less than legumes for captured and non-fed aquacultured seafood, to the load comparable to beef for fed aquacultured shrimps and prawns. Scenario analysis of NF for Japan provided realistic options for consumers with some concrete examples of more sustainable diets. While this study contributed to include international trade to NF calculation and to provide more detailed information on NF of seafood, NF models have some limitations for accuracy of their estimations. Considering trade-offs between nitrogen issues and other environmental issues are also required in the use of NF. Yet, NF is a practical tool to help policy makers and consumers to understand that, through our choices on food and other commodities, we can reduce the human-induced Nr and mitigate nitrogen pollution both in our local areas and in the areas where our food and other commodities come from.

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Appendix 1: Supplementary Information for Chapter 2

A1.1 Supplementary Methods

A1.1.1 Multi-region input–output analysis – a basic introduction

The notion of an environmental footprint encompasses the enumeration of the upstream supply-chains underlying consumer goods and services (Wiedmann and Minx, 2008). Recently, environmental footprints are to an increasing degree being determined using input–output analysis(Lenzen, 2014; McBain, 2015), due to the latter's ability to probe into supply-chain networks. Examples are the ubiquitous carbon footprints (Hertwich and Peters, 2009; Minx *et al*., 2009; Wiedmann, 2009a), but also ecological footprints (Bicknell *et al*., 1998; Lenzen and Murray, 2001; Turner *et al*., 2007), land appropriation (Hubacek and Giljum, 2003), water footprints (Daniels *et al*., 2011), employment footprints (Alsamawi *et al*., 2014), biodiversity footprints (Lenzen *et al*., 2012b), and material footprints (Wiedmann *et al.*, 2015). Feng *et al.* (2011) have shown how the use of input–output analysis can avoid truncation errors for the example of global water footprints, confirming earlier truncation error studies (Lenzen and Dey, 2000; Lenzen, 2008). Similarly, Huang *et al.* (2009) show how criteria in product footprinting standards can only be met if input–output analysis is used. The current state of art combines detailed, specific, bottom-up process analysis and complete, top-down input–output analysis into a hybrid method (Alvarez-Gaitan *et al*., 2013; Bullard *et al*., 1978; Crawford, 2008; Lenzen and Crawford, 2009; Lenzen, 2009; Lin, 2009; Malik *et al*., 2015; Moran *et al*., 2015; Moskowitz and Rowe, 1985; Nakamura *et al*., 2008; Rodríguez-Alloza *et al*., 2015; Rowley *et al*., 2009; Strømman, 2009; Strømman *et al*., 2009; Suh and Nakamura, 2007; Suh *et al*., 2004; Wiedmann *et al*., 2011).

Input–output analysis is a macroeconomic technique aimed at unravelling intersectoral relationships in complex economies (Leontief, 1966). It was conceived by Nobel Prize laureate Wassily Leontief (Leontief, 1941, 1936). Since Leontief's breakthrough, input–output analysis has been used in numerous environmental analyses (Hoekstra, 2010), and input–output databases are now routinely published by statistical bureaux around the world and governed by the United Nations (UN) and the European Union (EU) standards (Eurostat, 2008; UN, 2009, 1999).

Table A.1 Schematic of an input–output intermediate transactions matrix for a simplified 5-sector economy.

	Agriculture	Mining	Manufacturing	Utilities	Services
Agriculture					
Mining			Iron ore for steel making		
Manufacturing			Steel for train making		Train for railway services
Utilities					
Services					

In essence, an input–output table is a square matrix **T** with the same industry sectors in its rows and columns, and with each element T_{ij} recording the monetary transaction value of the supply of products made by industry *i* for use in industry *j* (Table A.1). These transactions are called intermediate transactions because goods and services end up for further processing in the using industries. A transactions table **T** can be used to trace supply chains underpinning the production of consumer goods and services, a prerequisite for life-cycle assessment and footprinting. For example, the provision of a railway transport service requires the existence of a train (Table A.1). The production of a train requires steel, and steel is made from iron ore. Combining the three production stages, one can understand intuitively how to work out in principle how much iron ore is required indirectly to provide railway transport service (Dixon, 1996; Duchin, 1992; Murray and R. Wood, 2010). Input–output transaction matrices **T** are complemented with final transactions (or so-called final demand) matrices **y**, showing how goods and services produced by industries are finally used by households and other economic agents.

Mathematically, input–output analysis proceeds as follows (Miller and Blair, 2009): The input–output balance of the economy is written as

$$\mathbf{x} = \mathbf{T1} + \mathbf{y}, \qquad (1)$$

where **T** is a $N \times N$ transactions matrix, **y** is a $N \times 1$ final demand vector, and **x** is a $N \times 1$ vector called gross output. The N×1 vector **1** is a summation operator summing entries of

$\mathbf{T}$ along one row. The input–output balance translates into the fundamental input–output relationship as

$$\mathbf{x} - \mathbf{T1} = \mathbf{y} \iff \mathbf{x} - \mathbf{A}\hat{\mathbf{x}}\mathbf{1} = \mathbf{y} \iff \mathbf{Ix} - \mathbf{Ax} = \mathbf{y} \iff (\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y}$$
$$\iff \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \ , \qquad (2)$$

where $\mathbf{I}$ is an $N \times N$ identity matrix, the circumflex (^) symbol denotes vector diagonalisation, and $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ is called the direct requirements matrix. Equation 2 provides a means to quantify how much gross output is needed to satisfy – directly and indirectly, via the economy's entire supply-chain network – a given bundle $\mathbf{y}$ of finally demanded goods and services. The matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the famous Leontief inverse.

In order to determine environmental footprints expressed in a physical variable (for example CO_2 emissions, material, land or water use, or threatened species) the input–output matrices need to be extended with matching matrices in physical units, so-called satellite accounts (Forssell, 1998; Leontief, 1970). Such accounts are now also being routinely published by some statistical agencies (for example in Australia by the Australian Bureau of Statistics (ABS, 2013, 2012, 2011, 2001, 1999, 1998)), and governed by UN standards (UNSD, 2014).

Mathematically, the physical extension is facilitated by converting a $1{\times}N$ satellite account $\mathbf{Q}$ into a $1{\times}N$ physical coefficients matrix $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$, which is then pre-multiplied with the fundamental input–output relationship according to

$$\mathbf{Q} = \mathbf{qx} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{my} \ , \qquad (3)$$

where the $1{\times}N$ vector $\mathbf{m}$ hold so-called physical multipliers, that can be pre-multiplied with final demand in order to yield the direct and indirect impacts in terms of the physical variable expressed in the satellite account, as a direct consequence of the purchasing activities reflected in final demand $\mathbf{y}$. In this sense, the product $\mathbf{my}$ is the consumption perspective representation of the physical satellite $\mathbf{Q}$, and $\mathbf{qx}$ is its production perspective representation. Both $\mathbf{qx}$ and $\mathbf{my}$ sum up to the same total, but in contrast to $\mathbf{qx}$ which slices $\mathbf{Q}$ according to producing entities delineated in $\mathbf{x}$, $\mathbf{my}$ slices $\mathbf{Q}$ according to consuming entities. This is the perspective asked for in the concept of a footprint (Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008). Hence input–output multipliers $\mathbf{m}$ are being used to enumerate the environmental consequences of consumption activities defined in form of a final demand vector $\mathbf{y}$.

Table A.2 Schematic of an input–output intermediate transactions matrix for a simplified 5-sector 3-country economy. A = Australia, B = Belgium and C = China are countries. Ag = Agriculture, Mn = Mining, Mf = Manufacturing, Ut = Utilities, Sv = Services.

	Ag A	MnA	Mf A	Ut A	Sv A	Ag B	MnB	Mf B	Ut B	Sv B	Ag C	MnC	Mf C	Ut C	Sv C
Agriculture A															
Mining A													1 – Iron ore		
Manufacturing A															
Utilities A															
Services A															
Agriculture B															
Mining B															
Manufacturing B															
Utilities B															
Services B															
Agriculture C															
Mining C															
Manufacturing C										3 – Trains			2 – Steel		
Utilities C															
Services C															

More recently, multi-region input–output (MRIO) analysis (Leontief and Strout, 1963) has been used to capture international trade in footprinting exercises (Ewing *et al.*, 2012; Peters and Hertwich, 2006; Steen-Olsen *et al.*, 2012; Wiedmann, 2009b). Other studies have equipped MRIO analysis with an uncertainty calculus (Lenzen *et al.*, 2010; Wilting, 2012). In essence, an MRIO account is identical to a single-region input–output (SRIO) account (Table A.1), but it is extended to cover multiple regions (Table A.2). MRIO systems are extended with environmental information in the same way as single-region systems (Zhou, 2010).

The example supply chain described for the SRIO table in Table A.1 also works for a multi-region setting as in Table A.2. Iron ore extracted in Australia is shipped to China to first make steel, and the train cars, which are then exported to Belgium for providing local railway services.

Especially given the increasing globalisation of markets, and the integration of supply-chain across multiple global actors, SRIO exercises have been shown to be associated with significant errors due to the inherent assumption that imports are produced using domestic production recipes (Lenzen *et al.*, 2004). As a result, and aided by recent advances in computational power, both in terms of RAM and runtime improvements through parallelisation, a number of global MRIO frameworks have been developed for widespread use (see overviews in Murray and Lenzen, 2013; Tukker and Dietzenbacher, 2013).

A1.2 Supplementary Figures and Tables

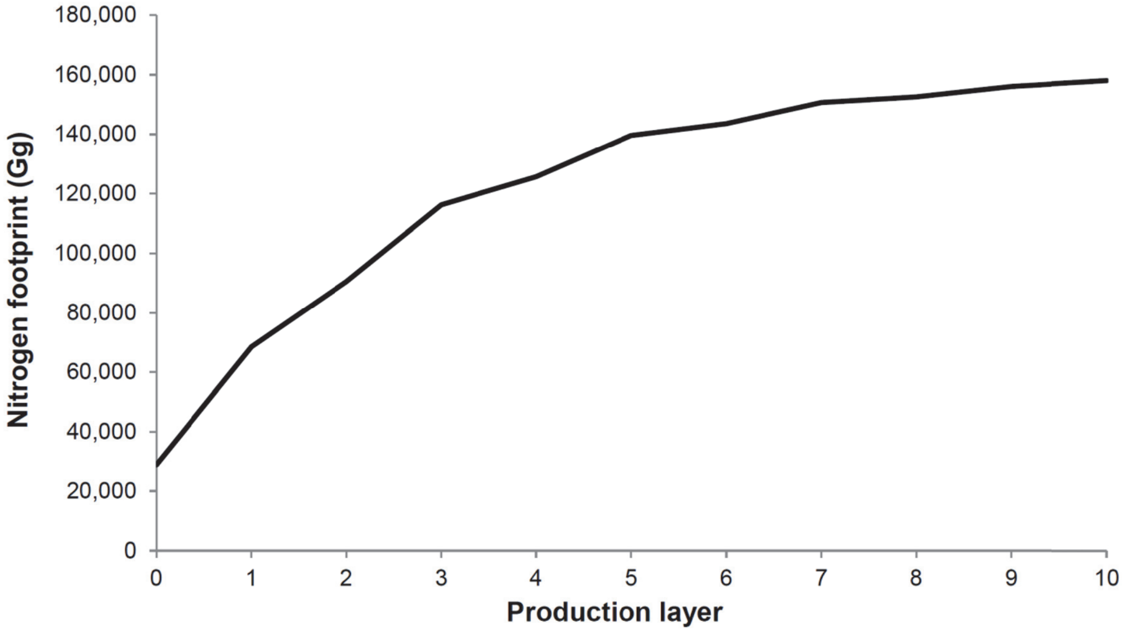

Figure A.1 Global nitrogen footprint as a function of supply-chain tier (production layer in input–output parlance). Even after including up to 3rd-tier supply chains (in the order of millions of individual supply chains), only about 50% completeness of a country's or product's nitrogen footprint assessment is achieved. Up to 8 tiers have to be enumerated in order to achieve acceptable completeness of more than 90%.

Table A.3 Correspondence of crop and livestock types across FAO and IFA databases, and the IPCC N model.

Crop/livestock name (FAO)	Fertilizer (IFA)	Residue (IPCC)
Wheat	Wheat	Wheat
Rice, paddy	Rice	Rice
Barley	Other Cereals	Barley
Maize	Maize	Maize
Popcorn	Other Cereals	Grains
Rye	Other Cereals	Rye
Oats	Other Cereals	Grains
Millet	Other Cereals	Millet
Sorghum	Other Cereals	Sorghum
Buckwheat	Other Cereals	Grains
Quinoa	Other Cereals	Grains
Fonio	Other Cereals	Grains
Triticale	Other Cereals	Grains
Canary seed	Other Cereals	Grains
Grain, mixed	Other Cereals	Grains
Cereals, nes	Other Cereals	Grains
Potatoes	Root and Tubers	Potatoes
Sweet potatoes	Root and Tubers	Tubers

Cassava	Root and Tubers	Tubers
Yautia (cocoyam)	Root and Tubers	Tubers
Taro (cocoyam)	Root and Tubers	Tubers
Yams	Root and Tubers	Tubers
Roots and tubers, nes	Root and Tubers	Tubers
Sugar cane	Sugar Crops	Non-N-fixing forages
Sugar beet	Sugar Crops	excluded
Sugar crops, nes	Other Crops	excluded
Beans, dry	Other Crops	Dry beans
Broad beans, horse beans, dry	Other Crops	Beans and Pulses
Peas, dry	Other Crops	Beans and Pulses
Chick peas	Other Crops	Beans and Pulses
Cow peas, dry	Other Crops	Beans and Pulses
Pigeon peas	Other Crops	Beans and Pulses
Lentils	Other Crops	Beans and Pulses
Bambara beans	Other Crops	Beans and Pulses
Vetches	Other Crops	Beans and Pulses
Lupins	Other Crops	Beans and Pulses
Pulses, nes	Other Crops	Beans and Pulses
Brazil nuts, with shell	Other Crops	excluded
Cashew nuts, with shell	Other Crops	excluded
Chestnut	Other Crops	excluded
Almonds, with shell	Other Crops	excluded
Walnuts, with shell	Other Crops	excluded
Pistachios	Other Crops	excluded
Kola nuts	Other Crops	excluded
Hazelnuts, with shell	Other Crops	excluded
Areca nuts	Other Crops	excluded
Nuts, nes	Other Crops	excluded
Soybeans	Soybean	Soyabean
Groundnuts, with shell	Other Oilseeds	excluded
Coconuts	Other Oilseeds	excluded
Oil, palm fruit	Oil Palm	excluded
Olives	Other Oilseeds	excluded
Karite nuts (sheanuts)	Other Oilseeds	excluded
Castor oil seed	Other Oilseeds	excluded
Sunflower seed	Other Oilseeds	excluded
Rapeseed	Other Oilseeds	excluded
Tung nuts	Other Oilseeds	excluded
Jojoba seed	Other Oilseeds	excluded
Safflower seed	Other Oilseeds	excluded
Sesame seed	Other Oilseeds	excluded
Mustard seed	Other Oilseeds	excluded
Poppy seed	Other Oilseeds	excluded
Melonseed	Other Oilseeds	excluded
Tallowtree seed	Other Oilseeds	excluded
Kapok fruit	Fiber Crops	excluded
Seed cotton	Fiber Crops	excluded
Linseed	Other Oilseeds	excluded
Hempseed	Other Oilseeds	excluded
Oilseeds nes	Other Oilseeds	excluded
Cabbages and other brassicas	Vegetables	excluded
Artichokes	Vegetables	excluded
Asparagus	Vegetables	excluded
Lettuce and chicory	Vegetables	excluded
Spinach	Vegetables	excluded
Cassava leaves	Vegetables	excluded
Tomatoes	Vegetables	excluded
Cauliflowers and broccoli	Vegetables	excluded

Pumpkins, squash and gourds	Vegetables	excluded
Cucumbers and gherkins	Vegetables	excluded
Eggplants (aubergines)	Vegetables	excluded
Chillies and peppers, green	Vegetables	excluded
Onions, shallots, green	Vegetables	excluded
Onions, dry	Vegetables	excluded
Garlic	Vegetables	excluded
Leeks, other alliaceous vegetables	Vegetables	excluded
Beans, green	Vegetables	Beans and Pulses
Peas, green	Vegetables	Beans and Pulses
Vegetables, leguminous nes	Vegetables	excluded
String beans	Vegetables	excluded
Carrots and turnips	Vegetables	excluded
Okra	Vegetables	excluded
Maize, green	Maize	Maize
Mushrooms and truffles	Vegetables	excluded
Chicory roots	Other Crops	excluded
Carobs	Fruits	excluded
Vegetables, fresh nes	Vegetables	excluded
Bananas	Fruits	excluded
Plantains	Fruits	excluded
Oranges	Fruits	excluded
Tangerines, mandarins, clementines, satsumas	Fruits	excluded
Lemons and limes	Fruits	excluded
Grapefruit (inc. pomelos)	Fruits	excluded
Fruit, citrus nes	Fruits	excluded
Apples	Fruits	excluded
Pears	Fruits	excluded
Quinces	Fruits	excluded
Apricots	Fruits	excluded
Cherries, sour	Fruits	excluded
Cherries	Fruits	excluded
Peaches and nectarines	Fruits	excluded
Plums and sloes	Fruits	excluded
Fruit, stone nes	Fruits	excluded
Fruit, pome nes	Fruits	excluded
Strawberries	Fruits	excluded
Raspberries	Fruits	excluded
Gooseberries	Fruits	excluded
Currants	Fruits	excluded
Blueberries	Fruits	excluded
Cranberries	Fruits	excluded
Berries nes	Fruits	excluded
Grapes	Fruits	excluded
Watermelons	Vegetables	excluded
Melons, other (inc.cantaloupes)	Vegetables	excluded
Figs	Fruits	excluded
Mangoes, mangosteens, guavas	Fruits	excluded
Avocados	Fruits	excluded
Pineapples	Fruits	excluded
Dates	Fruits	excluded
Persimmons	Fruits	excluded
Cashewapple	Fruits	excluded
Kiwi fruit	Fruits	excluded
Papayas	Fruits	excluded
Fruit, tropical fresh nes	Fruits	excluded
Fruit, fresh nes	Fruits	excluded
Coffee, green	Other Crops	excluded
Cocoa, beans	Other Crops	excluded

Tea	Other Crops	excluded
Maté	Other Crops	excluded
Hops	Other Crops	excluded
Pepper (piper spp.)	Other Crops	excluded
Chillies and peppers, dry	Other Crops	excluded
Vanilla	Other Crops	excluded
Cinnamon (canella)	Other Crops	excluded
Cloves	Other Crops	excluded
Nutmeg, mace and cardamoms	Other Crops	excluded
Anise, badian, fennel, coriander	Other Crops	excluded
Ginger	Other Crops	excluded
Spices, nes	Other Crops	excluded
Peppermint	Other Crops	excluded
Pyrethrum, dried	Other Crops	excluded
Flax fibre and tow	Fiber Crops	excluded
Hemp tow waste	Fiber Crops	excluded
Jute	Fiber Crops	excluded
Bastfibres, other	Fiber Crops	excluded
Ramie	Fiber Crops	excluded
Sisal	Fiber Crops	excluded
Agave fibres nes	Fiber Crops	excluded
Manila fibre (abaca)	Fiber Crops	excluded
Fibre crops nes	Fiber Crops	excluded
Tobacco, unmanufactured	Other Crops	excluded
Rubber, natural	Other Crops	excluded
Fodder grass	Other Crops	excluded
Buffaloes	excluded	excluded
Cattle, dairy	excluded	excluded
Cattle, non-dairy	excluded	excluded
Sheep	excluded	excluded
Goats	excluded	excluded
Swine, market	excluded	excluded
Swine, breeding	excluded	excluded
Chickens, layers	excluded	excluded
Chickens, broilers	excluded	excluded
Ducks	excluded	excluded
Turkeys	excluded	excluded
Horses	excluded	excluded
Asses	excluded	excluded
Mules	excluded	excluded
Camels	excluded	excluded
Llamas	excluded	excluded

Table A.4 Data availability across countries/areas and data categories.

Country/area name	Crop (FAO)	Livestock (FAO)	Fertilizer (IFA)	MRIO (Eora)	Air emissions (EDGAR)	Food supply (FAO)	Food waste (FAO)	Wastewater treatment (OECD, 2013; Galloway *et al.*, 2014; Stevens *et al.*, 2014; UNEP and WHRC, 2007; Wu, 1999)
Afghanistan	y	y	ROW	y	y	ind	6	ROW
Albania	y	y	ROW	y	y	ind	1	OECD
Algeria	y	y	ROW	y	y	ind	5	ROW
American Samoa	y	y	ROW		y			

Andorra	y		ROW	y		South	1	OECD
Angola	y	y	ROW	y	y	ind	4	ROW
Anguilla					y			
Antarctica					y			
Antigua and Barbuda	y	y	ROW	y	y	ind	7	ROW
Argentina	y	y	ind	y	y	ind	7	ROW
Armenia	y	y	ROW	y	y	ind	1	OECD
Aruba		y		y	y	Caribbean	7	ROW
Australia	y	y	ind	y	y	ind	2	OECD
Austria	y	y	EU	y	y	ind	1	ind
Azerbaijan	y	y	ROW	y	y	ind	1	OECD
Bahamas	y	y	ROW	y	y	ind	7	ROW
Bahrain	y	y	ROW	y	y	Western Asia	5	ROW
Bangladesh	y	y	ind	y	y	ind	6	ROW
Barbados	y	y	ROW	y	y	ind	2	OECD
Belarus	y	y	ind	y	y	ind	1	OECD
Belgium	y	y	EU	y	y	ind	1	ind
Belize	y	y	ROW	y	y	ind	7	ROW
Benin	y	y	ROW	y	y	ind	4	ROW
Bermuda	y	y	ROW	y	y	ind	2	OECD
Bhutan	y	y	ROW	y	y	Southern	6	ROW
Bolivia (Plurinational State of)	y	y	ROW	y	y	ind	7	ROW
Bosnia and Herzegovina	y	y	ROW	y	y	ind	1	OECD
Botswana	y	y	ROW	y	y	ind	4	ROW
Bouvet Island					y			
Brazil	y	y	ind	y	y	ind	7	ROW
British Indian Ocean Territory					y			
British Virgin Islands	y	y	ROW	y		Caribbean	2	OECD
Brunei Darussalam	y	y	ROW	y	y	ind	6	ROW
Bulgaria	y	y	EU	y	y	ind	1	OECD
Burkina Faso	y	y	ROW	y	y	ind	4	ROW
Burundi	y	y	ROW	y	y	Eastern	4	ROW
Cabo Verde	y	y	ROW	y	y	ind	4	ROW
Cambodia	y	y	ROW	y	y	ind	6	ROW
Cameroon	y	y	ROW	y	y	ind	4	ROW
Canada	y	y	ind	y	y	ind	2	ind
Cayman Islands	y	y	ROW	y	y	Caribbean	2	OECD
Central African Republic	y	y	ROW	y	y	ind	4	ROW
Chad	y	y	ROW	y	y	ind	4	ROW
Chile	y	y	ind	y	y	ind	7	ind
China	y	y	ind	y	y	ind	3	OECD
Christmas Island					y			
Cocos (Keeling) Islands					y			
Colombia	y	y	ROW	y	y	ind	7	ROW
Comoros	y	y	ROW		y			
Congo	y	y	ROW	y	y	ind	4	ROW
Cook Islands	y	y	ROW		y			
Costa Rica	y	y	ROW	y	y	ind	7	ROW
Côte d'Ivoire	y	y	ROW	y	y	ind	4	ROW
Croatia	y	y	ROW	y	y	ind	1	OECD
Cuba	y	y	ROW	y	y	ind	7	ROW
Cyprus	y	y	EU	y	y	ind	1	OECD
Czech Republic	y	y	EU	y	y	ind	1	ind
North Korea (Democratic People's Republic of Korea)	y	y	ROW	y	y	ind	6	ROW
DR Congo (Democratic Republic of the Congo)	y	y	ROW	y	y	Middle Africa	4	ROW
Denmark	y	y	EU	y	y	ind	1	ind

Djibouti	y	y	ROW	y	y	ind	4	ROW
Dominica	y	y	ROW		y	ind		
Dominican Republic	y	y	ROW	y	y	ind	7	ROW
Ecuador	y	y	ROW	y	y	ind	7	ROW
Egypt	y	y	ind	y	y	ind	5	ROW
El Salvador	y	y	ROW	y	y	ind	7	ROW
Equatorial Guinea	y	y	ROW		y			
Eritrea	y	y	ROW	y	y	Eastern	4	ROW
Estonia	y	y	EU	y	y	ind	1	ind
Ethiopia	y	y	ROW	y	y	ind	4	ROW
Falkland Islands (Malvinas)		y			y			
Faroe Islands	y	y	ROW		y			
Fiji	y	y	ROW	y	y	ind	7	ROW
Finland	y	y	EU	y	y	ind	1	ind
France	y	y	EU	y	y	ind	1	ind
French Guiana	y	y	ROW		y			
French Polynesia	y	y	ROW	y	y	ind	7	ROW
French Southern Territories					y			
Gabon	y	y	ROW	y	y	ind	4	ROW
Gambia	y	y	ROW	y	y	ind	4	ROW
Georgia	y	y	ROW	y	y	ind	1	OECD
Germany	y	y	EU	y	y	ind	1	ind
Ghana	y	y	ROW	y	y	ind	4	ROW
Gibraltar					y			
Greece	y	y	EU	y	y	ind	1	ind
Greenland		y		y	y	Northern	1	OECD
Grenada	y	y	ROW		y	ind		
Guadeloupe	y	y	ROW		y			
Guam	y	y	ROW		y			
Guatemala	y	y	ROW	y	y	ind	7	ROW
Guinea	y	y	ROW	y	y	ind	4	ROW
Guinea-Bissau	y	y	ROW		y	ind		
Guyana	y	y	ROW	y	y	ind	7	ROW
Haiti	y	y	ROW	y	y	ind	7	ROW
Heard Island and McDonald					y			
Honduras	y	y	ROW	y	y	ind	7	ROW
China, Hong Kong SAR	y	y	ROW	y	y	ind	3	OECD
Hungary	y	y	EU	y	y	ind	1	ind
Iceland	y	y	ROW	y	y	ind	1	ind
India	y	y	ROW	y	y	ind	6	ROW
Indonesia	y	y	ind	y	y	ind	6	ROW
Iran (Islamic Republic of)	y	y	ind	y	y	ind	6	ROW
Iraq	y	y	ROW	y	y	ind	5	ROW
Ireland	y	y	EU	y	y	ind	1	ind
Israel	y	y	ROW	y	y	ind	5	ind
Italy	y	y	EU	y	y	ind	1	ind
Jamaica	y	y	ROW	y	y	ind	7	ROW
Japan	y	y	ind	y	y	ind	3	ind
Jordan	y	y	ROW	y	y	ind	5	ROW
Kazakhstan	y	y	ROW	y	y	ind	5	ROW
Kenya	y	y	ROW	y	y	ind	4	ROW
Kiribati	y	y	ROW		y	ind		
Kuwait	y	y	ROW	y	y	ind	5	ROW
Kyrgyzstan	y	y	ROW	y	y	ind	5	ROW
Laos (Lao People's Democratic Republic)	y	y	ROW	y	y	ind	6	ROW
Latvia	y	y	EU	y	y	ind	1	OECD
Lebanon	y	y	ROW	y	y	ind	5	ROW

Lesotho	y	y	ROW	y	y	ind	4	ROW
Liberia	y	y	ROW	y	y	ind	4	ROW
Libya	y	y	ROW	y	y	Northern	5	ROW
Liechtenstein	y	y	ROW	y		Western	1	OECD
Lithuania	y	y	EU	y	y	ind	1	OECD
Luxembourg	y	y	EU	y	y	ind	1	ind
China, Macao SAR	y	y	ROW	y	y	ind	3	OECD
Madagascar	y	y	ROW	y	y	ind	4	ROW
Malawi	y	y	ROW	y	y	ind	4	ROW
Malaysia	y	y	ind	y	y	ind	6	ROW
Maldives	y		ROW	y	y	ind	6	ROW
Mali	y	y	ROW	y	y	ind	4	ROW
Malta	y	y	EU	y	y	ind	1	OECD
Marshall Islands	y		ROW		y			
Martinique	y	y	ROW		y			
Mauritania	y	y	ROW	y	y	ind	4	ROW
Mauritius	y	y	ROW	y	y	ind	4	ROW
Mayotte					y			
Mexico	y	y	ind	y	y	ind	7	ind
Micronesia (Federated States of)	y	y	ROW		y			
Monaco				y		France	1	OECD
Mongolia	y	y	ROW	y	y	ind	5	ROW
Montenegro	y	y	ROW	y		ind	1	OECD
Montserrat	y	y	ROW		y			
Morocco	y	y	ind	y	y	ind	5	ROW
Mozambique	y	y	ROW	y	y	ind	4	ROW
Myanmar	y	y	ROW	y	y	ind	6	ROW
Namibia	y	y	ROW	y	y	ind	4	ROW
Nauru	y	y	ROW		y			
Nepal	y	y	ROW	y	y	ind	6	ROW
Netherlands	y	y	EU	y	y	ind	1	ind
Netherlands Antilles		y	ROW	y	y	ind	7	ROW
New Caledonia	y	y	ROW	y	y	ind	1	OECD
New Zealand	y	y	ROW	y	y	ind	2	ind
Nicaragua	y	y	ROW	y	y	ind	7	ROW
Niger	y	y	ROW	y	y	ind	4	ROW
Nigeria	y	y	ROW	y	y	ind	4	ROW
Niue	y	y	ROW		y			
Norfolk Island					y			
Northern Mariana Islands					y			
Norway	y	y	ROW	y	y	ind	1	ind
Gaza Strip (Occupied Palestinian	y	y	ROW	y		Western Asia	6	ROW
Oman	y	y	ROW	y	y	ind	5	ROW
Pakistan	y	y	ind	y	y	ind	6	ROW
Palau					y			
Panama	y	y	ROW	y	y	ind	7	ROW
Papua New Guinea	y	y	ROW	y	y	Melanesia	7	ROW
Paraguay	y	y	ROW	y	y	ind	7	ROW
Peru	y	y	ROW	y	y	ind	7	ROW
Philippines	y	y	ind	y	y	ind	6	ROW
Pitcairn					y			
Poland	y	y	EU	y	y	ind	1	ind
Portugal	y	y	EU	y	y	ind	1	ind
Puerto Rico	y	y	ROW		y			
Qatar	y	y	ROW	y	y	Western Asia	6	ROW
South Korea (Republic of Korea)	y	y	ROW	y	y	ind	3	ind
Moldova (Republic of)	y	y	ROW	y	y	ind	1	OECD

Réunion	y	y	ROW		y			
Romania	y	y	EU	y	y	ind	1	OECD
Russia (Russian Federation)	y	y	ind	y	y	ind	1	OECD
Rwanda	y	y	ROW	y	y	ind	4	ROW
Saint Helena, Ascension and Tristan da Cunha	y	y	ROW		y			
Saint Kitts and Nevis	y	y	ROW		y	ind		
Saint Lucia	y	y	ROW		y	ind		
Saint Pierre and Miquelon	y	y	ROW		y			
Saint Vincent and the Grenadines	y	y	ROW		y	ind		
Samoa	y	y	ROW	y	y	ind	7	ROW
San Marino				y		Italy	1	OECD
Sao Tome and Principe	y	y	ROW	y	y	ind	4	ROW
Saudi Arabia	y	y	ROW	y	y	ind	5	ROW
Senegal	y	y	ROW	y	y	ind	4	ROW
Serbia	y	y	ROW	y		ind	1	OECD
Seychelles	y	y	ROW	y	y	Eastern	4	ROW
Sierra Leone	y	y	ROW	y	y	ind	4	ROW
Singapore	y	y	ROW	y	y	Malaysia	3	OECD
Slovakia	y	y	EU	y	y	ind	1	ind
Slovenia	y	y	EU	y	y	ind	1	ind
Solomon Islands	y	y	ROW		y	ind		
Somalia	y	y	ROW	y	y	Eastern	4	ROW
South Africa	y	y	ind	y	y	ind	4	ROW
South Sudan	y a)	y a)	ROW	y		ind a)	4	ROW
South Georgia and the South Sandwich Islands					y			
Spain	y	y	EU	y	y	ind	1	ind
Sri Lanka	y	y	ROW	y	y	ind	6	ROW
Sudan	y a)	y a)	ROW	y	y	ind a)	4	ROW
Suriname	y	y	ROW	y	y	ind	7	ROW
Swaziland	y	y	ROW	y	y	ind	4	ROW
Sweden	y	y	EU	y	y	ind	1	ind
Switzerland	y	y	ROW	y	y	ind	1	ind
Syria (Syrian Arab Republic)	y	y	ROW	y	y	Western Asia	5	ROW
China, Taiwan Province of	y	y	ROW	y	y	ind	3	OECD
Tajikistan	y	y	ROW	y	y	ind	5	ROW
Thailand	y	y	ind	y	y	ind	6	ROW
TFYR Macedonia (The former Yugoslav Republic of Macedonia)	y	y	ROW	y	y	ind	1	OECD
Timor-Leste	y	y	ROW		y	ind		
Togo	y	y	ROW	y	y	ind	4	ROW
Tokelau	y	y	ROW		y			
Tonga	y	y	ROW		y			
Trinidad and Tobago	y	y	ROW	y	y	ind	2	OECD
Tunisia	y	y	ROW	y	y	ind	5	ROW
Turkey	y	y	ind	y	y	ind	5	ind
Turkmenistan	y	y	ROW	y	y	ind	5	ROW
Turks and Caicos Islands					y			
Tuvalu	y	y	ROW		y			
Uganda	y	y	ROW	y	y	ind	4	ROW
Ukraine	y	y	ind	y	y	ind	1	OECD
UAE (United Arab Emirates)	y	y	ROW	y	y	ind	5	ROW
UK (United Kingdom)	y	y	EU	y	y	ind	1	ind
Tanzania, United Republic of	y	y	ROW	y	y	ind	4	ROW
USA (United States of America)	y	y	ind	y	y	ind	2	ind

United States Minor Outlying Islands					y			
United States Virgin Islands	y	y	ROW					
Uruguay	y	y	ROW	y	y	ind	7	ROW
Uzbekistan	y	y	ind	y	y	ind	5	ROW
Vanuatu	y	y	ROW	y	y	ind	7	ROW
Venezuela (Bolivarian Republic of)	y	y	ROW	y	y	ind	7	ROW
Viet Nam	y	y	ind	y	y	ind	6	ROW
Virgin Islands_British					y			
Virgin Islands_USA					y			
Wallis and Futuna Islands	y	y	ROW		y			
Western Sahara	y	y	ROW		y			
Yemen	y	y	ROW	y	y	ind	5	ROW
Zambia	y	y	ROW	y	y	ind	4	ROW
Zimbabwe	y	y	ROW	y	y	ind	4	ROW

Note: "y" means data exist, "ind" means individual country's data were used, "EU" means data for the European Union countries were used, "OECD" means average data for OECD countries were used, and "ROW" means data for the rest of the world (no removal for waste water treatment) were used. Numbers indicate 1: Europe incl. Russia, 2: America and Oceania, 3: Industrialized Asia, 4: sub-Saharan Africa, 5: North Africa, West and Central Asia, 6: South and Southeast Asia, and 7: Latin America.

a) FAOSTAT data of Sudan (former) were divided into Sudan and South Sudan in proportion to gross output of agricultural sectors in 2010 except yield and protein supply per capita, for which the same values of Sudan (former) were used for both countries.

Table A.5 Production layer decomposition of the NF for the world countries. The table shows the decomposition of the nitrogen footprint in terms of the upstream supply chains. Percentages show the contribution of the supply chain tier to the total nitrogen emissions. Emissions of layer 0 refer to direct emissions from sectors of final sale ($q_i y_i$ explained in Section 2.3.2) and emissions of layer 1 refer to induced emissions from first layer of production ($q_i A_{ij} y_j$).

Country	Layer 0 (% of total)	Layer 1 (% of total)	Layer 2 (% of total)	Layer 3 (% of total)	Re-maining Layers (% of total)	Most significant Layer	Sector
Afghanistan	41	33	16	6	5	Layer 0	Agriculture
Albania	21	35	21	10	12	Layer 1	Food and beverages
Algeria	34	38	16	6	6	Layer 1	Agriculture
Andorra	0	19	23	18	39	Layer 2	Food and beverages
Angola	18	35	24	12	12	Layer 1	Food and beverages
Antigua	16	28	21	11	23	Layer 1	Food and beverages
Argentina	7	6	49	5	33	Layer 2	Meat and meat products
Armenia	14	30	22	13	21	Layer 1	Food and beverages
Aruba	3	16	24	15	41	Layer 2	Hotels and restaurants
Australia	26	27	1	25	20	Layer 1	Fresh meat
Austria	15	20	8	22	35	Layer 3	Food products and beverages
Azerbaijan	23	32	21	11	12	Layer 1	Agriculture
Bahamas	21	22	20	9	28	Layer 1	Food and beverages
Bahrain	25	22	16	10	27	Layer 0	Food and beverages

Bangladesh	17	30	22	14	18	Layer 1	Food and beverages
Barbados	20	27	19	10	24	Layer 1	Food and beverages
Belarus	83	13	2	1	1	Layer 0	Agriculture
Belgium	11	11	14	20	45	Layer 3	Food products and beverages
Belize	40	35	12	4	9	Layer 0	Agriculture
Benin	25	43	20	7	5	Layer 1	Food and beverages
Bermuda	18	29	20	11	22	Layer 1	Food and beverages
Bhutan	12	37	27	12	12	Layer 1	Food and beverages
Bolivia	16	20	0	47	16	Layer 3	Fresh and processed meat
Bosnia and Herzegovina	19	30	21	12	17	Layer 1	Food and beverages
Botswana	29	42	16	6	7	Layer 1	Food and beverages
Brazil	20	4	37	4	35	Layer 2	Beef and other live animals
British Virgin Islands	9	32	22	14	24	Layer 1	Food and beverages
Brunei	21	26	20	11	22	Layer 1	Food and beverages
Bulgaria	20	28	20	12	19	Layer 1	Agriculture
Burkina Faso	17	27	22	14	20	Layer 1	Food and beverages
Burundi	12	29	25	15	19	Layer 1	Food and beverages
Cambodia	31	44	16	5	4	Layer 1	Agriculture
Cameroon	41	35	15	5	4	Layer 0	Agriculture
Canada	21	24	19	10	26	Layer 1	Food products, beverages and tobacco
Cape Verde	12	39	25	11	13	Layer 1	Food and beverages
Cayman Islands	13	26	23	12	25	Layer 1	Food and beverages
Central African Republic	21	43	22	8	5	Layer 1	Food and beverages
Chad	30	30	21	10	10	Layer 0	Agriculture
Chile	18	18	1	35	29	Layer 3	Meat
China	37	25	15	8	14	Layer 0	Livestock and livestock products
Colombia	21	71	0	4	4	Layer 1	Meat and fish
Congo	20	34	23	11	11	Layer 1	Food and beverages
Costa Rica	33	24	17	8	17	Layer 0	Agriculture
Croatia	16	27	21	13	23	Layer 1	Food and beverages
Cuba	22	46	20	7	6	Layer 1	Food and beverages
Cyprus	22	27	18	11	23	Layer 1	Food and beverages
Czech Republic	20	22	5	23	31	Layer 3	Food products and beverages
Cote dIvoire	52	26	12	5	5	Layer 0	Agriculture
North Korea	34	34	18	8	7	Layer 0	Food and beverages
DR Congo	21	35	23	11	11	Layer 1	Food and beverages
Denmark	15	31	18	11	25	Layer 1	Production of meat and meat products
Djibouti	26	41	19	7	6	Layer 1	Food and beverages
Dominican Republic	39	37	13	4	6	Layer 0	Agriculture
Ecuador	29	13	35	8	14	Layer 2	Cattle, live animals and animal products
Egypt	33	37	18	7	6	Layer 1	Food and beverages
El Salvador	26	33	20	9	13	Layer 1	Food and beverages

Eritrea	16	45	24	9	6	Layer 1	Food and beverages
Estonia	21	23	4	25	28	Layer 3	Food products and beverages
Ethiopia	99	0	0	0	0	Layer 1	Agriculture
Fiji	35	38	13	5	9	Layer 1	Agriculture
Finland	12	14	7	24	44	Layer 3	Food products and beverages
France	17	22	4	27	30	Layer 3	Food products and beverages
French Polynesia	17	22	19	14	29	Layer 1	Food and beverages
Gabon	24	26	20	11	18	Layer 1	Food and beverages
Gambia	14	42	25	10	9	Layer 1	Food and beverages
Georgia	48	7	19	9	17	Layer 0	Live animals and animal products
Germany	17	27	19	11	26	Layer 1	Food products
Ghana	59	28	7	3	3	Layer 0	Agriculture
Greece	23	24	5	22	26	Layer 1	Food products and beverages
Greenland	21	19	18	13	29	Layer 0	Personal and other services
Guatemala	53	27	10	4	7	Layer 0	Agriculture
Guinea	34	51	12	2	1	Layer 1	Food and beverages
Guyana	4	16	30	14	35	Layer 2	Food and beverages
Haiti	28	44	18	6	4	Layer 1	Food and beverages
Honduras	23	27	20	12	18	Layer 1	Agriculture
Hong Kong	6	6	8	21	59	Layer 3	Wearing apparel
Hungary	24	26	2	25	23	Layer 1	Food products and beverages
Iceland	12	37	17	9	25	Layer 1	Food and beverages
India	36	36	1	15	12	Layer 1	Other livestock products
Indonesia	35	42	13	4	5	Layer 1	Milled grain and flour
Iran	43	11	14	9	23	Layer 0	Cattle, sheep, goats & other live animals except poultry
Iraq	53	32	9	3	3	Layer 0	Agriculture
Ireland	12	13	2	35	37	Layer 3	Food products and beverages
Israel	8	8	17	12	55	Layer 2	Processing of meat and poultry
Italy	14	15	7	23	42	Layer 3	Food products and beverages
Jamaica	24	31	20	9	17	Layer 1	Food & Beverages
Japan	10	29	18	14	30	Layer 1	General eating and drinking places (except coffee shops)
Jordan	26	27	18	11	18	Layer 1	Food & Beverages
Kazakhstan	41	27	19	7	6	Layer 0	Agriculture
Kenya	44	46	1	6	3	Layer 1	Poultry
Kuwait	58	11	9	5	16	Layer 0	Electricity, gas and steam
Kyrgyzstan	40	39	1	13	7	Layer 0	Meat (live weight)
Laos	49	31	12	4	3	Layer 0	Agriculture
Latvia	30	32	2	17	20	Layer 1	Products of agriculture, hunting and related services
Lebanon	27	29	18	9	17	Layer 1	Food & Beverages

Lesotho	14	42	26	10	8	Layer 1	Food & Beverages
Liberia	33	29	20	9	9	Layer 0	Agriculture
Libya	27	32	20	10	10	Layer 1	Food & Beverages
Liechtenstein	2	21	22	17	38	Layer 2	Food & Beverages
Lithuania	22	32	6	24	17	Layer 1	Food products and beverages
Luxembourg	16	10	17	12	45	Layer 2	Food & Beverages
Macao SAR	3	18	21	16	42	Layer 2	Textiles and Wearing Apparel
Madagascar	68	20	7	2	2	Layer 0	Agriculture
Malawi	54	27	11	4	4	Layer 0	Agriculture
Malaysia	27	23	17	10	23	Layer 0	Hotels & restaurants
Maldives	12	26	21	13	29	Layer 1	Public Administration
Mali	28	40	20	7	5	Layer 1	Food & Beverages
Malta	18	20	6	25	31	Layer 3	Food products and beverages
Mauritania	13	56	21	7	4	Layer 1	Food & Beverages
Mauritius	6	7	30	15	42	Layer 2	Knitted or crocheted fabrics; wearing apparel
Mexico	29	32	1	24	14	Layer 1	Food industry
Monaco	0	24	25	18	33	Layer 2	Public Administration
Mongolia	29	32	19	10	10	Layer 1	Agriculture
Montenegro	4	31	26	16	22	Layer 1	Food & Beverages
Morocco	27	38	19	8	7	Layer 1	Food & Beverages
Mozambique	38	39	15	5	3	Layer 1	Agriculture
Myanmar	21	20	17	13	28	Layer 0	Agriculture
Namibia	15	39	21	11	13	Layer 1	Food & Beverages
Nepal	39	40	13	4	3	Layer 1	Agriculture
Netherlands	10	10	21	20	38	Layer 2	Food products and beverages
Netherlands Antilles	2	43	4	24	26	Layer 1	Construction services
New Caledonia	19	31	21	11	18	Layer 1	Food & Beverages
New Zealand	2	3	57	4	34	Layer 2	Meat and meat products
Nicaragua	26	33	20	10	11	Layer 1	Agriculture
Niger	13	39	25	12	11	Layer 1	Food & Beverages
Nigeria	24	26	18	12	21	Layer 1	Agriculture
Norway	16	17	5	24	39	Layer 3	Food products and beverages
Gaza Strip	8	28	25	15	24	Layer 1	Food & Beverages
Oman	26	32	19	9	14	Layer 1	Food & Beverages
Pakistan	33	41	17	6	4	Layer 1	Food & Beverages
Panama	26	32	19	8	15	Layer 1	Food & Beverages
Papua New Guinea	36	26	14	7	16	Layer 0	Education, Health and Other Services
Paraguay	20	3	46	4	27	Layer 2	Beef
Peru	27	29	1	24	19	Layer 1	Agricultural, Hunting and Forestry products
Philippines	38	45	9	3	6	Layer 1	Milled grain and flour
Poland	33	26	2	20	19	Layer 0	Products of agriculture, hunting and related services
Portugal	15	20	9	23	34	Layer 3	Food products and beverages

Qatar	35	31	15	6	12	Layer 0	Food & Beverages
South Korea	16	21	14	10	39	Layer 1	Transportation and warehousing
Moldova	52	38	8	1	1	Layer 0	Agriculture
Romania	30	30	1	20	18	Layer 0	Products of agriculture, hunting and related services
Russia	37	32	15	7	8	Layer 0	Agriculture, hunting, forestry and fishing
Rwanda	16	47	23	8	6	Layer 1	Food & Beverages
Samoa	12	37	24	12	15	Layer 1	Food & Beverages
San Marino	0	31	27	18	25	Layer 1	Public Administration
Sao Tome and Principe	14	33	23	13	17	Layer 1	Food & Beverages
Saudi Arabia	26	34	19	8	14	Layer 1	Food & Beverages
Senegal	28	50	15	4	3	Layer 1	Food & Beverages
Serbia	5	20	21	17	37	Layer 2	Food & Beverages
Seychelles	16	36	20	10	17	Layer 1	Public Administration
Sierra Leone	9	27	22	15	27	Layer 1	Food & Beverages
Singapore	6	8	10	20	56	Layer 3	Food & beverage services
Slovakia	24	24	5	19	28	Layer 0	Products of agriculture, hunting and related services
Slovenia	19	23	4	21	34	Layer 1	Food products and beverages
Somalia	17	43	24	9	7	Layer 1	Food & Beverages
South Africa	21	17	29	11	22	Layer 2	Agricultural products
South Sudan	19	35	24	12	11	Layer 1	Food & Beverages
Spain	16	6	28	10	40	Layer 2	Products of agriculture
Sri Lanka	43	29	12	4	12	Layer 0	Agriculture
Sudan	22	38	22	10	8	Layer 1	Food & Beverages
Suriname	25	33	20	10	13	Layer 1	Electricity, Gas and Water
Swaziland	21	43	17	7	11	Layer 1	Food & Beverages
Sweden	14	15	3	27	42	Layer 3	Food products and beverages
Switzerland	12	12	12	22	42	Layer 3	Food products, beverages and tobacco products
Syria	24	25	18	12	21	Layer 1	Agriculture
Taiwan	23	22	17	12	27	Layer 0	Slaughtering & By-Products
Tajikistan	70	17	6	3	3	Layer 0	Agriculture
Thailand	16	33	23	12	16	Layer 1	Rice Milling
TFYR Macedonia	22	25	2	23	28	Layer 1	Products of agriculture, hunting and related services
Togo	38	34	16	6	6	Layer 0	Agriculture
Trinidad and Tobago	28	26	18	8	19	Layer 0	Food & Beverages
Tunisia	28	34	19	9	11	Layer 1	Food & Beverages
Turkey	33	37	4	16	10	Layer 1	Products of agriculture, hunting and related services
Turkmenistan	45	29	14	6	6	Layer 0	Products of agriculture, hunting and related services

Uganda	39	34	15	6	5	Layer 0	Agriculture
Ukraine	29	26	18	11	16	Layer 0	Agriculture
UAE	23	24	17	9	27	Layer 1	Food & Beverages
UK	26	24	2	17	30	Layer 0	Raising of dairy cattle and production of raw cow milk
Tanzania	52	31	11	3	2	Layer 0	Agriculture
USA	19	23	3	38	17	Layer 3	Animal (except poultry) slaughtering, rendering, and processing
Uruguay	22	2	49	2	25	Layer 2	Poultry and eggs, other animals and their products
Uzbekistan	44	29	18	6	4	Layer 0	Animal Husbandry
Vanuatu	15	45	21	9	10	Layer 1	Food & Beverages
Venezuela	13	16	1	39	31	Layer 3	Carne y derivados
Viet Nam	56	24	11	4	5	Layer 0	Other crops
Yemen	19	24	18	13	27	Layer 1	Food & Beverages
Zambia	30	37	19	7	7	Layer 1	Food & Beverages
Zimbabwe	52	22	12	6	8	Layer 0	Agriculture

Note: Even if the N-calculator were complete up to the 3rd tier, its truncation error would still be around 30%. If we assumed that this calculator were complete only up to tier 2, the truncation error would even be in the order of 50%, for example, our results of 50 kg cap^{-1} yr^{-1} for the Netherlands compared to 25 kg cap^{-1} yr^{-1} (Leach *et al*., 2012). Truncation errors are further discussed in Appendix 1.1.1.

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Appendix 2: Supplementary Methods for Chapter 3

A2.1 Values of the Reactive Nitrogen Flows of Seafood Categories for All Parameter Sets

Values for the Nr flows of seafood categories for all parameter sets not shown in Figure 3.1 is available as online supplementary data at http://dx.doi.org/10.1016/j.ecolind.2015.08.039.

A.2.2 Detailed Methods for the Calculation of Parameters δ and ε

A2.2.1 Calculation of ratios of fed aquacultured seafood in consumption (δ in Table 3.5)

1. Parameter set W

We defined the production of non-fed aquacultured seafood ($L_{\text{non-fed-aq}}$) related to Eq. (12) for each category as shown in Table B.1. We considered Antarctic krill (*Euphausia superba*) and Norwegian krill (*Meganyctiphanes norvegica*) as being for non-food use and excluded them from capture production. We then estimated δ from the 2009 data for all countries listed in FAO (2014a) excluding non-fed aquacultured seafood quantities from total aquacultured seafood quantities (Eq. (12)).

Table B.1 Definitions of non-fed aquacultured seafood used to calculate fed aquaculture ratio δ in Table 3.5.

Category of seafood (FAOSTAT group)	Species or species group included
Freshwater and diadromous fish	Aquacultured production of filter feeding carp, including Bighead carp (*Hypophthalmichthys nobilis*), Hoven's carp (*Leptobarbus hoeveni*), Mrigal carp (*Cirrhinus mrigala*), Mud carp (*Cirrhinus molitorella*), Nilem carp (*Osteochilus hasselti*), Silver carp (*Hypophthalmichthys molitrix*), Silver bighead carp not elsewhere included (*Hypophthalmichthys spp.*), Smallscale mud carp (*Cirrhinus microlepis*).
Crustaceans	Aquacultured production of FAO ISSCAAP groups other than "Shrimp, prawns" and "Freshwater crustaceans".
Cephalopods	N/A (all captured; including flying squid (*Ommastrephinae*), pencil squids (*Loliginidae*), octopus (*Octopodidae*), true cuttlefishes (*Sepiidae*), etc.)
Mollusks, other	All aquacultured production of the category is non-fed aquaculture (e.g. true oysters (*Ostreidae*), Venus clams (*Veneridae*), marine mussels (*Mytilidae*), and scallops (*Pectinidae*)).

Note: Categories not indicated above were considered to be fed aquaculture and capture fisheries only.

2. Parameter set J

Table B.2 shows a summary of estimated consumption quantities converted to live weight and ratios of fed aquacultured seafood to total consumption (δ) for Japan in 2009. We estimated δ from the three parts of Eq. (14)—domestic production ($L_{domestic}$), imported quantity ($\Sigma_k L_k^{\mathrm{im}}$), and exported quantity ($\Sigma_k L_k^{\mathrm{ex}} + \Sigma_k L_k^{\mathrm{re}}$)—taken from the 2009 data for Japan in FAO (2014a).

For domestic production, we defined non-fed aquacultured seafood ($L_{\text{non-fed-aq}}$) in Eq. (12) for each category in the same way as for parameter set W (Table B.1) and also excluded Antarctic krill (*Euphausia superba*) and Norwegian krill (*Meganyctiphanes norvegica*) from capture production. We then estimated the production of each source for each category.

For the import and export quantities of each category, we first converted data to live weight with the conversion ratios θ shown in Table B.3, then calculated the ratios of fed aquacultured seafood included in commodities, and finally estimated quantities of fed aquacultured seafood. For the converted weight of each species group utilized for roe-related commodities, we compared the converted live weight of roe-related commodities and that of all the other commodities, and counted only the bigger of the two. For the definition of fed-aquacultured–seafood-included commodities, we considered major fed aquacultured species: for import those listed by Tacon and Metian (2008) except the ones with a converted weight of less than one Gg; and for export the 2009 data of Japanese production given in FAO (2014a).

Table B.4 shows considered commodities for trading quantities. For the estimation of quantities of fed aquacultured seafood, we calculated ratios of fed aquacultured seafood in each importing commodity with a weighted average of the main trading partners' production that accounts for the top 90% or more, and the ratio in each exporting commodity from Japanese production.

Finally, using the calculated quantities for domestic production and trading commodities, we estimated the production of each source for each category with Eq. (13) and Eq. (14) to estimate δ with Eq. (12).

Table B.2 Consumption quantities in live weight for Japan used to calculate fed aquaculture ratios (δ) of parameter set J.

[ton (Mg)]

	Freshwater and diadromous fish	Demersal fish	Pelagic fish	Marine fish, other	Crust-aceans	Cepha-lopods	Mollusks, other
Total Consumption	710,664	1,897,390	2,717,712	1,927,076	425,372	583,043	948,184
Domestic production	313,132	681,639	2,251,072	252,175	84,663	394,177	819,291
Import estimate	469,962	1,377,950	787,013	1,776,463	349,733	317,488	271,345
Export estimate	72,430	162,196	320,373	101,561	9,023	128,622	142,452
Consumption of fed aquaculture	411,418	87,921	154,984	87,252	212,020	– [b]	– [b]
Domestic production	56,696	80,293	159,147	9,557	1,657	– [b]	– [b]
Import estimate	354,920	7,873	0	81,540	210,942	– [b]	– [b]
Export estimate	197	243	4,162	3,849	588	– [b]	– [b]
Ratio of fed aquaculture [a] (δ)	58%	5%	6%	5%	50%	0%	0%

Calculated from production and trade data taken from FAO (2014a) with the conversion ratios θ shown in Table B.3 and estimated fed aquaculture ratio in traded commodities (Table B.4).

[a] The ratio of "Consumption of fed aquaculture" over "Total Consumption".

[b] "Cephalopods" and "Mollusks, other", were considered to be non-fed aquaculture and capture fisheries.

Table B.3 Fresh conversion ratio (θ)

Category	Fresh conversion ratio (θ_k)
Frozen	
Salmon, dressed, gutted, head off	0.77
Trout, head on	0.71
Flatfish, dressed, gutted, head off	0.71
Cod, gutted, head off	0.59
Hake, dressed, gutted, head off	0.65
Alaska pollock, dressed, gutted, head off	0.46
Haddock, dressed, gutted, head off	0.62
Herring, whole, gutted, head off	0.66
Yellowfin tunas, gutted, head on	0.91
Skipjack tuna, gutted, head on	0.91
Marlin, gutted, head on	0.91
Swordfish, gutted, head off	0.76
Other tuna, gutted, head off	0.74
Mackerel, gutted, head off	0.68
Jack and horse mackerel, gutted, head off	0.61
Seabream, gutted, head off	0.68
Sea bass, gutted, head off	0.56
Eel, gutted, head on	0.90
Fillets	
Flatfish, skin off	0.38
Herring, skin off	0.46
Cod, skin off	0.31
Salmon, skin off	0.50
Tuna, skin off	0.28
Fish dried, whether or not salted	
Pilchard	0.38
Other fish	0.25
Fish salted, wet or in brine	
Cod	0.67
Other demersal	0.50
Freshwater fish	0.63
Herring	0.72
Mackerel	0.69
Anchovy	0.75
Salmon	0.67
Other pelagic	0.72
Marine fish, other	0.61 [a]
Smoked	
Herring	0.67
Salmon	0.52
Other smoked fish	0.62

Table B.3 (continued)

Category	Fresh conversion ratio (θ_k)
Fish dried, salted, or in brine	
Freshwater fish	0.44 [b]
Cod	0.46 [c]
Marine fish, other	0.43 [d]
Commodities not specified above	
Canned	0.55 [e]
Frozen	0.70 [f]
Fillet	0.34 [g]
Minced	0.20 [h]
Mix of minced and not minced	0.27 [i]
Eel preparation	0.61 [j]
Crustaceans preparation	0.45 [g]
Roes	0.04 [k]

Note: Ratios were estimated using data from FAO (2014b) unless otherwise mentioned.

[a] Average of "other demersal" and "other pelagic".

[b] Average of "fish dried, whether or not salted—other fish" and "fish salted, wet or in brine—freshwater fish".

[c] Average of "fish dried, whether or not salted—other fish" and "fish salted, wet or in brine—cod".

[d] Average of "fish dried, whether or not salted—other fish" and "fish salted, wet or in brine—marine fish, other".

[e] Estimated using data from Japanese food balance sheet 2009 (FAO, 2012).

[f] With assumption of being dressed, estimated using data from United States Department of Agriculture Economic Research Service (1992).

[g] Estimated using data from United States Department of Agriculture Economic Research Service (1992).

[h] Estimated using the conversion ratio set for quota calculation by the Ministry of Economy, Trade and Industry of Japan (2013)

[i] Average of "Fillet and Minced".

[j] Estimated using data from Sekine (2010) and FAO (2014a).

[k] Estimated from inquiry to the person involved.

Table B.4 Commodities considered for ratios of fed aquacultured seafood.

Category of seafood (FAOSTAT group) Commodity	Considered species	Import to Japan			Export from Japan	
		Converted live weight (L_k^{im}) [Mg]	Ratio of fed aquaculture (ρ_k^{im})	Major import partners (% of share [a])	Converted live weight (L_k^{im})	Ratio of fed aquaculture (ρ_k^{ex})
Demersal fish						
"Flatfishes, fresh or chilled, nei", "Flatfishes nei, frozen", "Flatfish nei, fillets, frozen"	Brill (*Scophthalmus rhombus*), Citharids nei (*Citharidae*), Flatfishes nei (*Pleuronectifrmes*), Pacific sanddab (*Citharichthys sordidus*), Tonguesfishes (*Cynoglossidae*)	35,428	0%	U.S.A. (41%), Iceland (12%), Canada (10%), Russia (9%), Greenland (5%), Netherlands (5%), Germany (5%), Spain (5%)	572	0%
"Halibuts, fresh or chilled, nei", "Halibuts nei, frozen"	Atlantic halibut (*Hippoglossus hippoglossus*), Bastard halibut (*Paralichthys olivaceus*), Bastard halibuts nei (*Paralichthys spp.*), Greenland halibut (*Reinhardtius hippoglossoides*), Indian halibut (*Psettodes erumei*), Pacific halibut (*Hippoglossus stenolepis*)	34,438	0%	U.S.A. (41%), Iceland (12%), Canada (10%), Russia (9%), Greenland (5%), Netherland (5%), Germany (5%), Spain (5%)	21	39.2%
"Plaices, fresh or chilled, nei", "Plaices, frozen, nei"	Alaska plaice (*Pleuronectes quadrituberculat.*), American plaice (*Hippoglossoides platessoides*), European plaice (*Pleuronectes platessa*)	0	0%	U.S.A. (41%), Iceland (12%), Canada (10%), Russia (9%), Greenland (5%), Netherland (5%), Germany (5%), Spain (5%)	1	0%
"Seabreams nei, fresh or chilled", "Seabreams, frozen"	Family of *Sparidae*	1,964	11.8%	Guinea (26%), Republic of Korea (17%), Liberia (15%), Morocco (12%), Argentina (11%), China (9%)	320	73.26%
"Puffer, fresh or chilled", "Puffer, frozen"	Atlantic puffers nei (*Sphoeroides spp.*), Northern puffer (*Sphoeroides maculatus*), Obscure pufferfish (*Takifugu obscurus*), Puffers nei (*Tetraodontidae*), Tiger pufferfish (*Takifugu rubripes*)	7,641	100%	China (100%)	–	–

Table B.4 (continued)

Category of seafood (FAOSTAT group) Commodity	Considered species	Import to Japan			Export from Japan	
		Converted live weight (L_k^{im}) [Mg]	Ratio of fed aquaculture (ρ_k^{im})	Commodity	Converted live weight (W_k^{im})	Converted live weight (L_k^{im}) [Mg]
Other commodities of demersal fish	Demersal fish not included above	1,298,479 [b]	0%	–	161,282	0%
Subtotal (fed aquaculture)	Demersal fish	1,377,950 (7,873)	0.57%	–	162,196 (243)	0.15%
Fresh water and diadromous fish						
"Eels, fresh or chilled", "Eels and elvers live", "Eels, frozen"	American eel (*Anguilla rostrata*), European eel (*Anguilla anguilla*), Japanese eel (*Anguilla japonica*), River eels nei (*Anguilla spp.*), Short-finned eel (*Anguilla australis*)	12,087	100%	China (55%), Taiwan (44%)	71	98.84%
"River eels, prepared or preserved, not minced, nei"	American eel (*Anguilla rostrata*), European eel (*Anguilla anguilla*), Japanese eel (*Anguilla japonica*), River eels nei (*Anguilla spp.*), Short-finned eel (*Anguilla australis*)	33,541	100%	China (97%)	--	--
" Salmon roes, cured "	Sockeye salmon (*Oncorhynchus nerka*)	81,200 [c]	0% [d]	USA (72%), Denmark (19%)	--	–

Table B.4 (continued)

Category of seafood (FAOSTAT group) Commodity	Considered species	Import to Japan Converted live weight (L_k^{im}) [Mg]	 Ratio of fed aquaculture (ρ_k^{im})	 Commodity	Export from Japan Converted live weight (W_k^{im})	 Converted live weight (L_k^{im}) [Mg]
"Salmon nei, not minced, prepared or preserved", "Salmons, smoked", "Atlantic and Danube salmons, fresh or chilled", "Pacific salmon, fresh or chilled", "Salmons, fresh or chilled, nei", "Trouts and chars live", "Salmonoids, frozen", "Trouts and chars, frozen", "Salmons nei, frozen", "Trouts and chars, fresh or chilled", "Salmonoids, fresh or chilled, nei", "Atlantic salmon and Danube salmon, frozen", "Salmonoids, dried, salted or in brine", "Pacific salmon, frozen, nei", "Salmonoids, salted or in brine", "Salmonoids fillets, frozen", "Salmon nei, not minced, prep. or pres, in airtight containers", "Salmons, fillets, dried, salted or in brine"	ISSCAAP group of "Salmons, trouts, smelts"	309,292	100%	Chile (77%), Norway (16%)	–	–
Trout and char, frozen	Rainbow trout (*Oncorhynchus kisutch*), Trout nei (*Salmo spp.*)	–	–	–	131	96.67%
"Salmon nei, not minced, prepared or preserved", "Pacific salmon, fresh or chilled", "Atlantic salmon and Danube salmon, frozen", "Pacific salmon, frozen, nei", "Sockeye salmon (red salmon)(Oncorhynchus nerka), frozen"	Chum salmon (*Oncorhynchus keta*)	–	–	–	72,228	0%
Other commodities of fresh water and diadromous fish	Fresh water and diadromous fish not included above	33,842	0%	–	0	0%
Subtotal (fed aquaculture)	Fresh water and diadromous fish	469,962 (354,920)	75.52%	–	72,430 (197)	0.27%

Table B.4 (continued)

Category of seafood (FAOSTAT group) / **Commodity**	**Considered species**	**Import to Japan**			**Export from Japan**	
		Converted live weight (L_k^{im}) [Mg]	Ratio of fed aquaculture (ρ_k^{im})	**Commodity**	Converted live weight (W_k^{im})	Converted live weight (L_k^{im}) [Mg]
Pelagic fish						
"Amberjack fillets, frozen"	Japanese amberjack (*Seriola quinqueradiata*)	–	–	–	6,268	66.4%
Other commodities of pelagic fish	Pelagic fish not included above	787,013	0%	–	314,106	0%
Subtotal (fed aquaculture)	Pelagic fish	787,013 (0)	0%	–	320,373 (4,162)	1.30%
Marine fish, other						
Commodities of marine fish with preparations, canned, cured, fresh, and frozen (fresh and frozen include fillets and whole)	Fish not identified (including Groundfishes, Pelagic fishes, Finfishes, Marine fishes)	1,776,463 (81,540)	4.59%	World	101,561 (3,849)	3.79%
Crustaceans						
"Shrimps and prawns, frozen, nei", "Shrimps and prawns, fresh or chilled, nei", "Shrimps, prawns, prepared or preserved, nei", "Shrimps and prawns, live"	ISSCAAP group of "Shrimps, prawns" [e] (Whiteleg shrimp (*Penaeus vannamei*), Giant tiger prawn (*Penaeus monodon*))	263086	79.06%	Vietnam (20%), Indonesia (18%), Thailand (16%), India (12%), China (8%), Canada (4%), Russian Federation (4%), Myanmar (3%), Greenland (3%), Malaysia (3%)	–	–
"Shrimps and prawns, dried, salted or in brine, nei"	Whiteleg shrimp (*Penaeus vannamei*), Giant tiger prawn (*Penaeus monodon*)	2,946	100%	China (57%), Vietnam (22%), Taiwan (15%)	–	–

Table B.4 (continued)

Category of seafood (FAOSTAT group) Commodity	Considered species	Import to Japan Converted live weight (L_k^{im}) [Mg]	Ratio of fed aquaculture (ρ_k^{im})	Commodity	Export from Japan Converted live weight (W_k^{im})	Converted live weight (L_k^{im}) [Mg]
"Shrimps and prawns, frozen, nei", "Shrimps and prawns, not frozen, nei", "Shrimps, prawns, prepared or preserved, nei"	ISSCAAP group of "Shrimps, prawns"	–	–	–	993	59.26%
Other commodities of crustaceans	Crustaceans not included above	83,701	0%	–	8,030	0%
Subtotal (fed aquaculture)	Crustaceans	349,733 (210,942)	60.32%	–	9,023 (588)	6.52%

Note: "nei" means "not elsewhere included", as used in FAO (2014a). Estimated from 2009 data in FAO (2014a).

[a] Estimated from import quantity data by item and country given by the Ministry of Finance of Japan (2010).

[b] Cod live weights are calculated with commodities of cod roes, which is larger than those of bodies.

[c] Wild caught salmon live weights are calculated with commodities of salmon roes, which is larger than those of bodies.

[d] Assumed that commodities of salmon roes are taken from wild caught salmon only.

[e] Assumed that shrimps from Asia are either whiteleg shrimp or giant tiger prawn, and giant tiger prawn (*Penaeus monodon*) imported from Thailand are fully fed aquaculture according to FAO Globefish (2014).

A2.2.2 Calculation of ratios of plant protein in feed (ε in Table 3.5)

Table B.5 Species considered for the ratio of plant protein in feed (*ε*)

Category	Ratio of plant protein in feed (weighted average)	Considered species	Production country/region
Freshwater and diadromous fish			
Parameter set W	54%	Non-filter feeding Chinese carp species (56%), Tilapia (13%), Catfish (10%), Salmon & Trout (9%), Miscellaneous freshwater carnivorous fish (4%)	No specific countries
Parameter set J	34%	Salmon (imported commodities) (58%), Trout (Imported commodities) (17%), Japanese eel (*Anguilla japonica*)	Salmon and Trout: Chile (77%); Norway (16%). Japanese eel: China (59%); Japan (33%); Taiwan (8%).
Demersal fish			
Parameter set W	19%	Flathead grey mullet (*Mugil cephalus*) (19%), Gilthead seabream (Sparus aurata) (12%), European seabass (*Dicentrarchus labrax*) (10%), Japanese seabass (*Lateolabrax japonicus*) (9%), Silver seabream (*Pagrus auratus*) (7%), Groupers nei (*Epinephelus spp.*) (6%), Turbot (*Psetta maxima)*(6%), Large yellow croaker (*Larimichthys croceus*) (6%), Bastard halibut (*Paralichthys olivaceus)*(5%), Red drum (*Sciaenops ocellatus*) (4%), Porgies, seabreams nei (*Sparidae*) (4%), Korean rockfish (*Sebastes schlegeli*) (3%), Lefteye flounders nei (*Bothidae*) (2%)	No specific countries
Parameter set J	0%	Silver seabream (*Pagrus auratus*) (80%), Tiger pufferfish (*Takifugu rubripes*) (14%)	Japan, China
Pelagic fish			
Parameter set W	0%	Japanese amberjack (*Seriola quinqueradiata*) (53%), Pompanos nei (*Trachinotus spp.*) (23%), Cobia (*Rachycentron canadum*) (11%), Amberjacks nei (*Seriola spp.*) (7%)	No specific countries
Parameter set J	0%	Japanese amberjack (*Seriola quinqueradiata*) (97%)	Japan
Marine fish, not identified	0%	Fish not identified (including Groundfishes, Pelagic fishes, Finfishes, Marine fishes)	No specific countries
Crustaceans			
Parameter set W	68%	ISSCAAP group of "Shrimps and prawns" and "fresh water crustaceans"	No specific countries
Parameter set J	53%	ISSCAAP group of "Shrimps and prawns"	India[a]

Note: weighted average with the 2009 data in FAO (2014a). Feed ingredients estimated from data in Tacon *et al*. (2011) and Tacon and Metian (2008). Plant protein ratio estimated from Córdova-Murueta and García-Carreño (2002), Raven, and Walker (1980) and FAO Fishery Industries Division (1986)

[a] Domestic aquaculture production with exported commodities subtracted accounts for less than 1%, and the majority is imported from the other Asian countries.

A2.3 References

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