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Drivers of global nitrogen emissions

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E-mail: arunima.malik@sydney.edu.au**Keywords:** structural decomposition analysis, nitrogen, drivers, input-output analysis, sustainability toolsSupplementary material for this article is available [online](#)**Abstract**

Nitrogen is crucial for sustaining life. However, excessive reactive nitrogen (Nr) in the form of ammonia, nitrates, nitrogen oxides or nitrous oxides affects the quality of water, air and soil, resulting in human health risks. This study aims to assess the drivers of Nr emissions by analysing six determinants: nitrogen efficiency (Nr emissions per unit of production), production recipe (inter-sectoral dependencies), final demand composition (consumption baskets of households), final demand destination (consumption vs. investment balance), affluence (final consumption per capita) and population. To this end, we construct a detailed multi-regional input-output database featuring data on international trade between 186 countries to undertake a global structural decomposition analysis of a change in global Nr emissions from 1997 to 2017. Our analysis shows that nitrogen efficiency has improved over the assessed time-period, however affluence, final demand destination and population growth have resulted in an overall increase in Nr emissions. We provide a global perspective of the drivers of nitrogen emissions at a detailed country level, and breakdown the change in emissions into contribution from domestic footprint and rest-of-world footprint. We highlight that food production coupled with growing international trade is increasing Nr emissions worldwide.

1. Introduction

The element nitrogen exists as a nitrogen gas (N₂) in its stable form, covering nearly 79% of the earth's atmosphere. In a balanced nitrogen cycle, this stable N₂ gas is converted to its reactive form (referred hereon as Nr, which includes all N species except N₂) by lightning (atmospheric nitrogen fixation) and microbes present in the soil (biological nitrogen fixation). Nr then travels through the environment, in turn changing its form and eventually converting back to N₂ by a process called denitrification (Vitousek *et al* 1997). Prior to the industrial revolution, the nitrogen fixation and denitrification processes were in equilibrium, thus Nr did not accumulate in the atmosphere (Ayres *et al* 1994). However, these processes are no longer in balance as humans

have devised methods for artificially fixing nitrogen in factories, primarily through the production of ammonia (NH₃) using the Haber-Bosch process. Undoubtedly, production of anthropogenic Nr, in the form of fertilisers, has been fundamental for sustaining the food demands of the growing global population (Mosier *et al* 2004). In addition to ammonia production, anthropogenic Nr is produced during fossil fuel combustion (in the form of nitrogen oxides NO_x). Cumulatively, these factors have contributed to an increase of Nr from 100 Tg N yr⁻¹ in 1970 to nearly 210 Tg N yr⁻¹ in 2010. The anthropogenic Nr creation is predicted to increase further to 267 Tg N yr⁻¹ by 2050 (Galloway *et al* 2004, 2013).

Nr is highly mobile and can travel through air, water and soil (Galloway *et al* 2003), which leads to stratospheric ozone loss; acidification of soils and

eutrophication of terrestrial and aquatic systems resulting in the loss of biodiversity; and pollution of surface and ground water rendering it unfit for human consumption (Galloway *et al* 2003). Undoubtedly, an excess of Nr affects ecosystems and causes human health risks. Excessive application of nitrogen fertilizers leads to a reduction in nitrogen-use efficiency (NUE). Nitrification inhibitors have been shown to be effective at improving NUE (Raza *et al* 2018, 2019).

To devise effective plans for integrated nitrogen management (Sutton *et al* 2021), there is a need to understand the impacts of Nr, and to quantify pressures & drivers of Nr emissions. Here, it is worth mentioning that the concept of ‘drivers’ is broad, and this term is used interchangeably in the literature on Nr emissions and leaching/runoff to describe drivers related to food production, food consumption, specific crop cultivation, crop strains, or specific agricultural practices. For the sake of brevity, we refer to Nr loss to the air and water as ‘Nr emissions’ in this article. Prior research on understanding the drivers of Nr emissions has focused on nitrogen footprint and related assessments (Leach *et al* 2012, Galloway *et al* 2014, Oita *et al* 2016, Shibata *et al* 2017, Hamilton *et al* 2018). ‘Nitrogen footprint’ is an indicator that captures Nr emissions from a life-cycle perspective for satisfying human consumption. The major drivers of Nr emissions are overuse of nitrogen fertilisers, affluence and population growth (Lassaletta *et al* 2014), however there is a limited understanding of contributions of a range of economic determinants that are responsible for driving the growth in Nr emissions at a global scale. One of the early assessments of drivers from an economic perspective was undertaken by Wier and Hasler (1999) for Denmark. Since then, a number of country-level assessments have been undertaken to analyse the change in Nr emissions over time (Deng *et al* 2016, Liu and Liang 2017), however none at a global scale, specifically for Nr emissions. This study fills this knowledge gap by undertaking an economic assessment of drivers of change in Nr emissions from 1997 to 2017 using a well-established technique called structural decomposition analysis (SDA).

SDA is instrumental in identifying the underlying drivers of a change in a variable over time. Specifically, SDA has been applied for decomposing the change in environmental variables such as energy use (Ma and Stern 2008, Weber 2009, Lan *et al* 2016, Dietzenbacher *et al* 2020), greenhouse gas emissions (De Haan 2001, Yamakawa and Peters 2011, Arto and Dietzenbacher 2014, Guo *et al* 2020), water use (Zhang *et al* 2012, Soligno *et al* 2018) and many others (see also (Hoekstra and Van Den Bergh 2003, Lenzen 2006, Su and Ang 2016) for details). This technique is based on macroeconomic input-output analysis (IOA) for unravelling inter-dependencies between regions and sectors (Miller and Blair 2009).

IOA relies on input-output tables that can either be single-region tables or multi-regional input–output (MRIO) tables. Single-region tables only capture transactions between sectors of a domestic economy - there are no trade matrices (export and import data are considered exogenous from the intermediate transactions matrix, and are therefore aggregated into a single vector each). A MRIO table, however, has explicit trade matrices between different countries (e.g. global MRIO table) or between different regions of a single country (e.g. sub-national MRIO table).

This study uses the Global MRIO Lab (Lenzen *et al* 2017) for constructing a customised MRIO table featuring 186 regions, with 25 sectors for each region, with time-series data from 1997 to 2017 to analyse the drivers of the change in Nr emissions from economic sectors including industries and agriculture, excluding those from sewage. Our study is novel in three ways: (a) we use a detailed MRIO model to undertake a comprehensive SDA for 186 countries over a 20 year period (prior footprint assessments have primarily focused on one-year); (b) we examine four reactive Nr species—nitrogen oxides (NO_x), nitrous oxides (N_2O), ammonia (NH_3) and nitrate (NO_3^-) separately; and (c) we provide a global perspective of both the domestic and rest-of-world nitrogen footprint for global regions over time. The findings presented in this study serve to understand the dynamics of international trade, global consumption and negative environmental impacts in the form of Nr emissions.

2. Methods

2.1. Structural decomposition analysis

MRIO tables form a core component of SDA. We construct a customised MRIO table featuring 187 regions (186 individual countries and 1 RoW region), with a range of primary, secondary and tertiary sectors for years 1997–2017 (see SI1 for a list (available online at stacks.iop.org/ERL/17/015006/mmedia)), using the Global MRIO Lab. The MRIO Lab is a cloud-computing environment that provides data and tools for constructing MRIO tables (Lenzen *et al* 2017). The MRIO table is converted from current to constant prices using the methodology described in appendix A of Lan *et al* (2016).

Unlike other decomposition techniques that use aggregated sector- and country-level data, SDA is based on detailed input-output data (see (Rose and Casler 1996, Hoekstra and Van Den Bergh 2003, Hoekstra and van Den Bergh 2006, Lenzen 2006)). In this work we apply SDA to a detailed time-series of MRIO matrices from 1997 to 2017, expressed in constant prices and couple these matrices with a nitrogen model (section 2.2) for undertaking MRIO-based SDA of Nr emissions. We decompose the change in

global Nr emissions ΔN into six mutually exclusive driving forces: Nr emissions intensity (\mathbf{n}), production structure (\mathbf{L}), final demand composition (\mathbf{u}), final

demand destination (\mathbf{v}), consumption per capita (y) and population (P). Mathematically, the variable N can be decomposed according to:

$$\Delta N = \underbrace{\Delta \mathbf{n} \mathbf{L} \mathbf{u} \mathbf{v} y P}_{\text{Changes due to technological improvements (nitrogen efficiency)}} + \underbrace{\mathbf{n} \Delta \mathbf{L} \mathbf{u} \mathbf{v} y P}_{\text{Changes due to re-structuring of supply chains (production structure)}} + \underbrace{\mathbf{n} \mathbf{L} \Delta \mathbf{u} \mathbf{v} y P}_{\text{Changes due to consumer choices (final demand composition)}} + \underbrace{\mathbf{n} \mathbf{L} \mathbf{u} \Delta \mathbf{v} y P}_{\text{Changes due to consumption-investment shifts (final demand destination)}} + \underbrace{\mathbf{n} \mathbf{L} \mathbf{u} \mathbf{v} \Delta y P}_{\text{Changes due to consumption per capita (affluence)}} + \underbrace{\mathbf{n} \mathbf{L} \mathbf{u} \mathbf{v} y \Delta P}_{\text{Changes due to population growth (population)}}.$$

Let K be the number of industry sectors and M be the number of final demand sectors. Then, \mathbf{n} is a $1 \times K$ vector of Nr emissions intensity (emissions per dollar of industry output); $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is a $K \times K$ matrix of Leontief's inverse, where \mathbf{I} is a $K \times K$ identity matrix and \mathbf{A} is a $K \times K$ matrix of direct coefficients (see Miller and Blair (2009)); $\mathbf{u} = \mathbf{f} (\mathbf{g}^{-1})$ is a $K \times M$ matrix of final demand composition, where \mathbf{f} is a $K \times M$ matrix of final demand and \mathbf{g} is a $1 \times M$ vector of total final demand by category; $\mathbf{v} = \mathbf{g} (F^{-1})$ is a $1 \times M$ vector of final demand by destination, where F is total final demand (1×1); y is total final demand per capita (1×1); and P is population.

We use the SDA method described by D&L (Dietzenbacher and Los 1998) because it is zero-robust (Wood and Lenzen 2006), non-parametrical and leaves no residuals (Lenzen 2006).

2.2. Nitrogen model

We construct a time-series of nitrogen satellites for years 1997–2017 for 186 countries, distinguishing four key nitrogen species: nitrogen oxides (NO_x), nitrous oxides (N_2O), ammonia (NH_3) (all three nitrogen species are released to air) and nitrate (NO_3^- , refers to Nr exportable to water bodies) (figure 1). These satellites are constructed by integrating Food and Agriculture Organisation (FAO)-based N emissions data (FAOSTAT 2021) with updated Emission Database for Global Atmospheric Research (EDGAR)-based air emission data (Crippa *et al* 2019a, b).

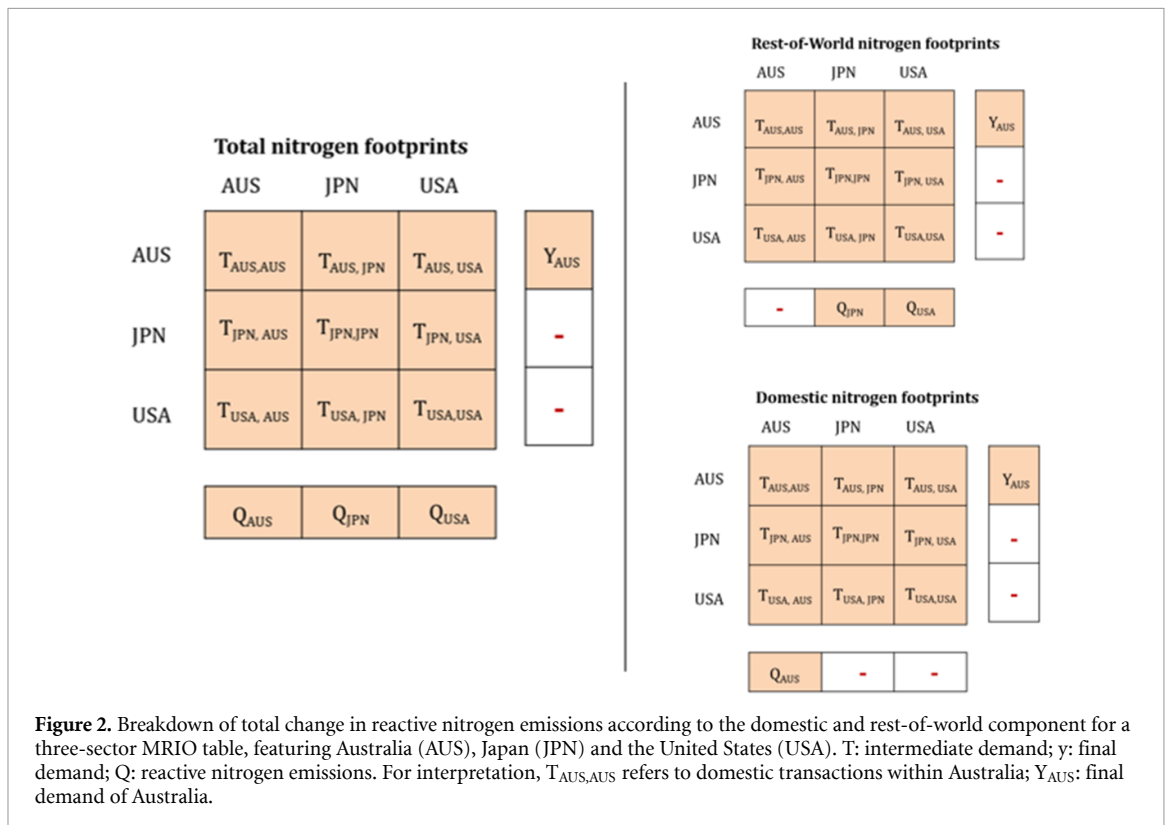
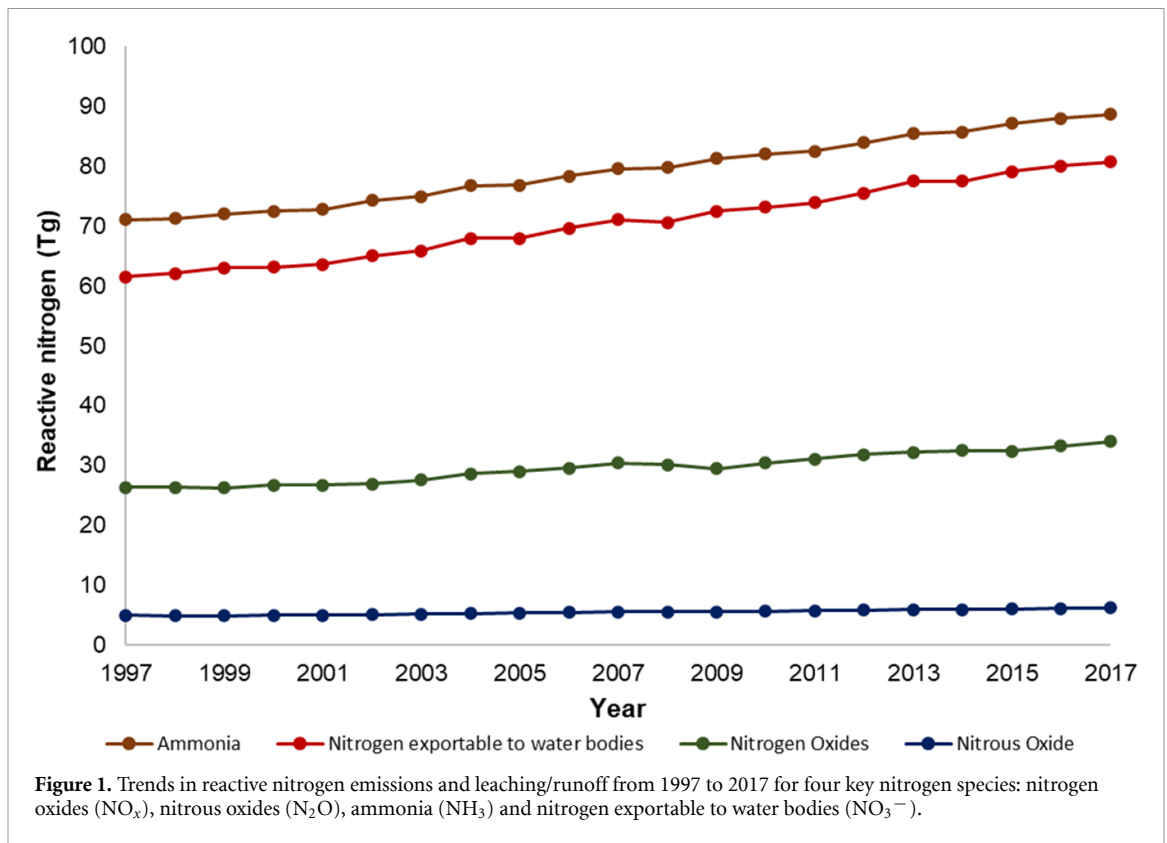
First, we gather detailed data on crop production (for 161 crops) and emissions from livestock production (including manure use and management for 17 livestock categories) from the FAO database (FAOSTAT 2021). Due to the paucity of data on crop-wise fertilizer use in the FAO database, crop-wise fertilizer was extracted from the International Fertiliser Industry Association (IFA) (Heffer 2013). For the fertiliser-derived Nr loss, we calculate fertiliser application ratios with IFA data on fertiliser use by crop/country categories and FAOSTAT data on harvested areas for corresponding crop/country categories. We

multiply the fertiliser application ratios and the year-sensitive FAOSTAT data on harvested areas to yield nitrogen applied as fertiliser. Nitrogen emission data are available for 17 livestock categories for around 200 countries from the FAO database (FAOSTAT 2021). We use a nitrogen flow model developed by the Intergovernmental Panel on Climate Change (IPCC 2006)—IPCC N emission equations to calculate the loss of NO_3^- , $\text{NH}_3 + \text{NO}_x$, and N_2O from fertiliser, residues, and livestock manure. Furthermore, we source additional data from the EDGAR database (v5.0) on N_2O , NH_3 , and NO_x for 23 industry sectors (including agriculture) and 231 countries to provide Nr loss data for all four N forms (see online Methods section of Oita *et al* 2016 for details).

Since the FAO dataset lacks information about Nr emissions from industry and transport, as a next step we source additional data from the EDGAR database to fill this gap. To this end, the FAO-based N satellites covering N emissions from crop and livestock are integrated with EDGAR-based N satellites encompassing emissions from industry and transport to obtain N satellites with complete sector coverage. To realise such integration, the FAO-based and EDGAR-based N satellites, distinguished by different source-specific sector and region classifications, are bridged to HSCPC classification of 6357 sectors by setting up a concordance matrix between the 178 FAO crop and livestock categories and each of the HSCPC sectors. Based on stoichiometric mass ratios, all FAO and EDGAR data are then converted into units of nitrogen content to construct the integrated N satellites. We link these satellites to the MRIO table for assessing the drivers of a change in Nr emissions from 1997 to 2017 using SDA (see Oita *et al* 2016) for a detailed description of the nitrogen model).

2.3. Change in domestic and rest-of-world footprint

In addition to structural decomposition of Nr emissions by six determinants (section 2.1), we geographically decompose the footprint into the



domestic component (hereon: domestic footprint: DF) and the international trade component (hereon: rest-of-world footprint: RoWF). Essentially, the sum of DF and RoWF yields the total Nr footprint. Figure 2

demonstrates the MRIO-based geographical decomposition for a three-region MRIO table.

For an illustrative scenario, considering Australia, total footprints $Q_{\text{Total}} = \mathbf{q}_{\text{World}} \mathbf{L}_{\text{World}} \mathbf{y}_{\text{AUS}}$

can be broken down into the domestic component $Q_{DF} = q_{AUS}L_{World}y_{AUS}$ and the rest-of-world component $Q_{RoWF} = q_{RoW}L_{World}y_{AUS}$. Here, q_{World} is the direct Nr emissions intensity for the world, q_{RoW} for the rest-of-world, L_{World} is the Leontief inverse for the world and y_{AUS} is the final demand of Australia.

3. Results and discussion

3.1. Growth in Nr emissions

Global Nr emissions have increased by 46 Teragrams (Tg) from 1997 to 2017. This increase is made up of an increase of 1.2Tg nitrous oxide (3%), 7.7Tg nitrogen oxides (17%), 17.7Tg ammonia (38%) and 19.2 Tg nitrogen exportable to water bodies (42%, figure 3).

A major underlying reason for the rise in NH_3 (38% increase) and NO_3^- (42% increase) emissions is due to the use of fertilisers for crop production—global demand for fertilizer nutrient use has increased from 184 million tonnes in 2015 to about 200 million tonnes in 2020 (FAO 2017). NO_3^- emissions are a key source of water pollution worldwide, predominantly caused by agricultural activities. Excess NO_3^- can accumulate in the environment, leading to contamination of drinking water (Galaviz-Villa *et al* 2010, Canter 2019), resulting in human health risks such as blue-baby syndrome and cancer (Tirado 2007).

Here, we assess the drivers of nitrogen emissions from an economic perspective, uncovering the regions and economic determinants that have facilitated the growth in emissions.

3.2. Drivers of Nr emissions

Nr emissions increased from 164 Tg in 1997 to 210 Tg in 2017, resulting in a total increase of 46 Tg (see stacked bar labelled 'All', figure 4, including all four Nr species). A breakdown of total Nr emissions (stacked bar 'All') reveals that the increase in emissions is due to the combined effect of changes in nitrogen efficiency (−202 Tg), production recipe (+4 Tg), final demand composition (+1 Tg), final demand destination (+70 Tg), affluence (+121 Tg) and population (+50 Tg) (refer to section 2.1 for a mathematical formulation of these drivers).

Nitrogen efficiency acts as a so-called 'retardant', whereas affluence and population are the key 'accelerators' of emissions. This effect is true across all Nr species. The influence of the six analysed determinants can be further assessed at a country-level, and here the use of a high-resolution MRIO database becomes evident (figure 5). Nitrogen efficiency has improved in the past two decades for all four Nr species (figure 4), and across all countries (figure 5), except in certain African nations. Despite improvements in nitrogen efficiency and implementation of nitrogen management strategies, emissions have continued to rise, fuelled by affluence and population growth. Here, strikingly, almost all nations have seen a growth in consumption per capita,

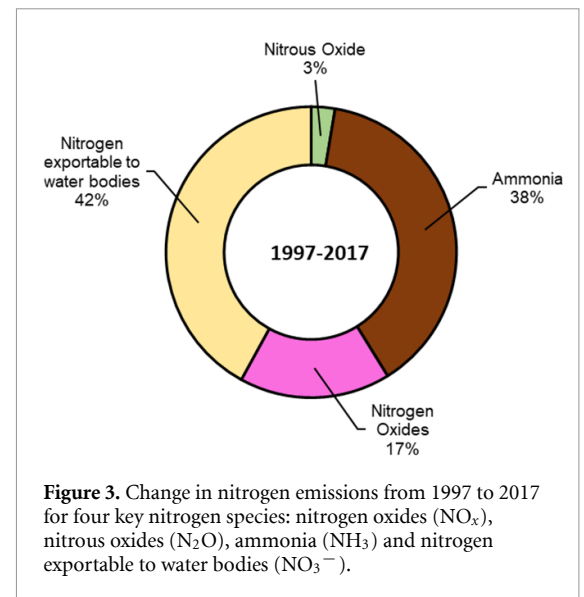


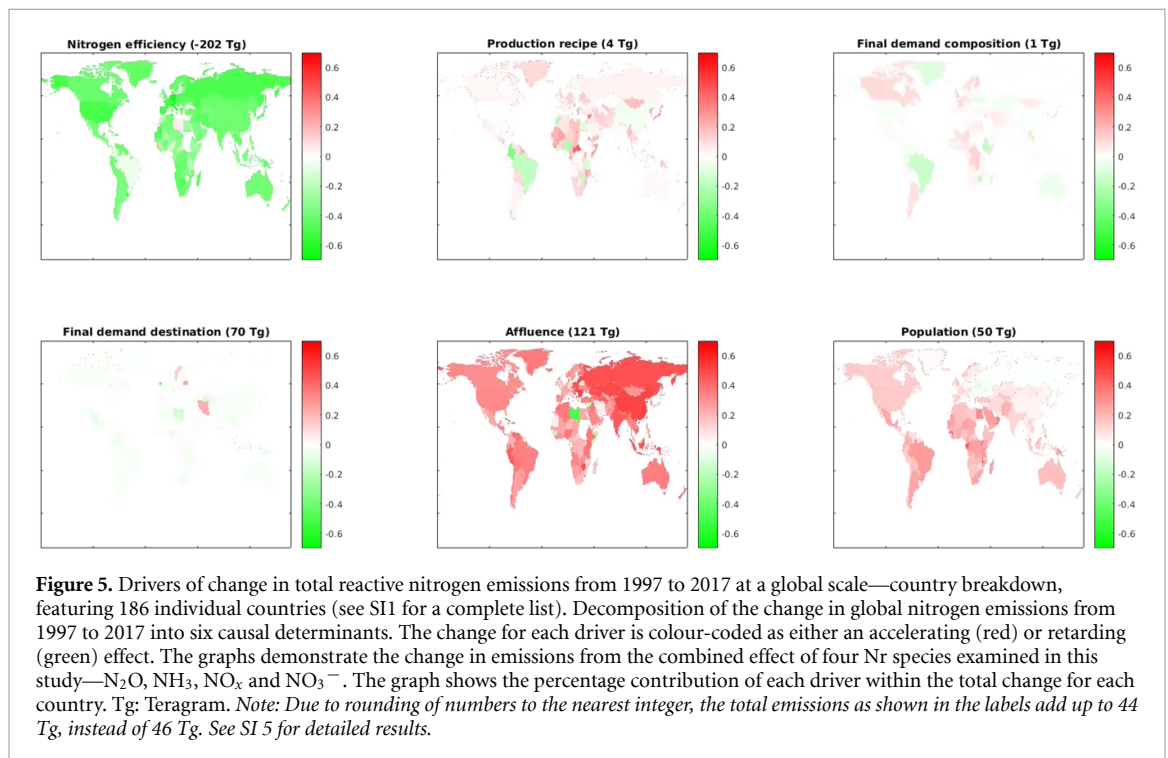
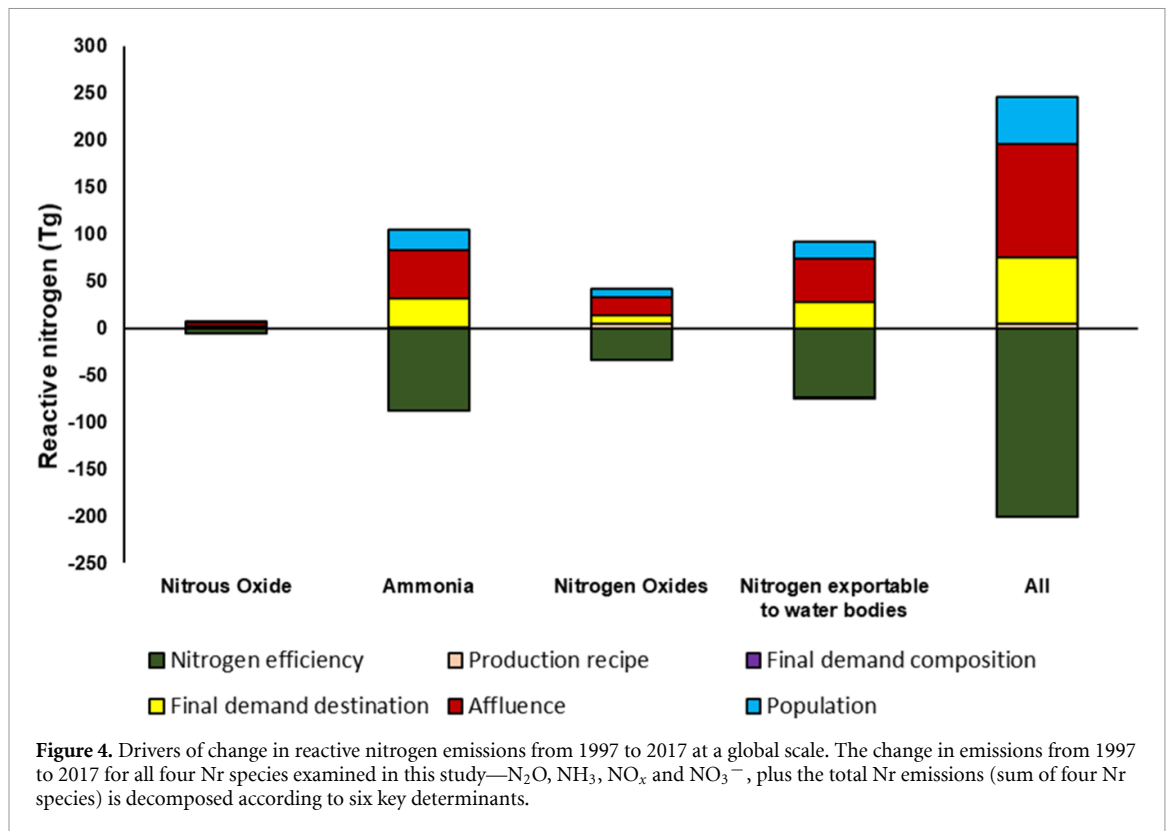
Figure 3. Change in nitrogen emissions from 1997 to 2017 for four key nitrogen species: nitrogen oxides (NO_x), nitrous oxides (N_2O), ammonia (NH_3) and nitrogen exportable to water bodies (NO_3^-).

except war-stricken African nations, such as Libya and Somalia. We examine each of the six determinants in further detail below.

3.2.1. Nitrogen efficiency

In an economic sense, nitrogen efficiency refers to the amount of Nr released into the air and water per dollar of output of an industry. For example, an improvement in nitrogen efficiency in the agricultural sector means that for every dollar of output of the agricultural sector, less Nr is released into the air or water. Since nitrogen efficiency has improved over time, this has had a positive effect in terms of decrease in Nr emissions and leaching/runoff, but as we show in the subsequent sections, the total emissions and leaching/runoff continue to rise due to a rise in affluence and population growth.

The key to attaining efficiency is to minimize the amount of nitrogen losses to the environment via leaching, volatilisation and denitrification (Yadav *et al* 2017). In the agricultural sector, this is primarily achieved by optimising the usage of nitrogen-based fertilisers. This involves curtailing on the levels of fertilisers applied to the soil and enhancing the uptake of the same by crops, whilst maintaining profitable yields (Cassman *et al* 2002). Furthermore, other management strategies include the use of specialist equipment for the precise delivery of the fertiliser to the crop; application of the fertiliser at a specific time to boost uptake by the plant; application of nitrification inhibitors that keep the nitrogen in the soil ready to be used by the plant when needed, thus reducing nitrogen losses by denitrification; and also irrigation and pest management to maintain healthy crops capable of extracting nitrogen from the soil (Snyder *et al* 2009, Davidson *et al* 2014, Tei *et al* 2020). The focus of these techniques has been on main cropping systems such as maize, rice and wheat, which provide almost 60% of the human dietary requirements (Cassman *et al* 2002, USDA 2007, Yang *et al* 2020). The choice



of the nitrogen management approach applied to an agricultural land depends on the area and location of the site, which in turn determines the most suitable fate and transport model for nitrogen. In the same vein, a nitrogen-budget and a mass-balance approach is often followed to recognize the likely environmental impacts of nitrogen and to devise management strategies (Follett 2008, Roy *et al* 2021).

In addition to the agricultural sector, nitrogen efficiency has also improved in the industry and manufacturing sectors. Nr emissions have reduced due to improvements in fuel efficiency of farm machinery in the past two decades (Snyder *et al* 2009). Furthermore, a number of technological improvements have ensured the efficiency of ammonia production (Smil 2002, Smith *et al* 2020). Efforts are

underway to further make efficiency gains by developing a less emissions intensive method for producing hydrogen—a key reactant for the production of ammonia (Snyder *et al* 2009, Ozturk and Dincer 2021).

Whilst nitrogen efficiency has improved for most world countries, certain African nations are still lagging behind (figure 5). Technological improvements have not penetrated the countries facing ongoing civil war such as Libya and Somalia. As an illustration we investigate the drivers of rise in nitrogen emissions in Congo. We select Congo based on documented evidence of a rise in emissions in the country due to land-use change, particularly deforestation and savannah burning. Land cleared by these activities is being diverted to agricultural activities (Chen *et al* 2010, Hickman *et al* 2011) or for the development of infrastructure projects, such as the expansion of road networks (Li *et al* 2014). Additionally, African wet-lands, specifically the Congo Basin, emit significant amounts of N₂O (Borges *et al* 2015). For Congo and many other nations, a rise in affluence and population have outpaced any improvements in nitrogen efficiency (see SI4).

3.2.2. Affluence and population

Globally, per-capita consumption has increased from 1997 to 2017 (figures 4 and 5). The consumption of eggs, milk and dairy products has increased drastically in the last four decades (Kearney 2010, Ritchie and Roser 2019), which has been driving a rise in Nr emissions (Westhoek *et al* 2015, Erisman *et al* 2018). Rising consumption has shown to be a key driver of negative environmental impacts for a range of indicators, as assessed in global and country-level assessments (Hamilton *et al* 2018, Wiedmann and Lenzen 2018, Ninpanit *et al* 2019, Wiedmann *et al* 2020).

The global population was 5.3 billion in 1990, increasing to nearly 7.6 billion in 2017 (United Nations 2017), and still increasing. Population growth has implications for food and resource production, which in turn drives Nr emissions. Almost all countries have experienced an increase in population, albeit slowly in Russia. Interestingly, Russia's population has declined due to low fertility and high mortality rates (Kuchins 2013, Sheludkov *et al* 2020). The impacts of population growth on the nitrogen cycle have been documented in detail elsewhere (Galloway *et al* 1994, Galloway and Cowling 2002, 2021). In particular, Galloway and Cowling (2021) on their “reflection on 200 years of nitrogen” state that a growing population translates to a growing demand for animal protein, which will further put pressure on the environment. A staggering 99% of the population growth from 2020 to 2050 is expected to occur in Asia and Africa, with the world population expected to reach about 10 billion by 2050. Interestingly, in contrast to the effects seen at a global level, where mostly

affluence has been a key driver of emissions (figure 4), Congo's emissions in particular have primarily been driven by population growth (see SI4).

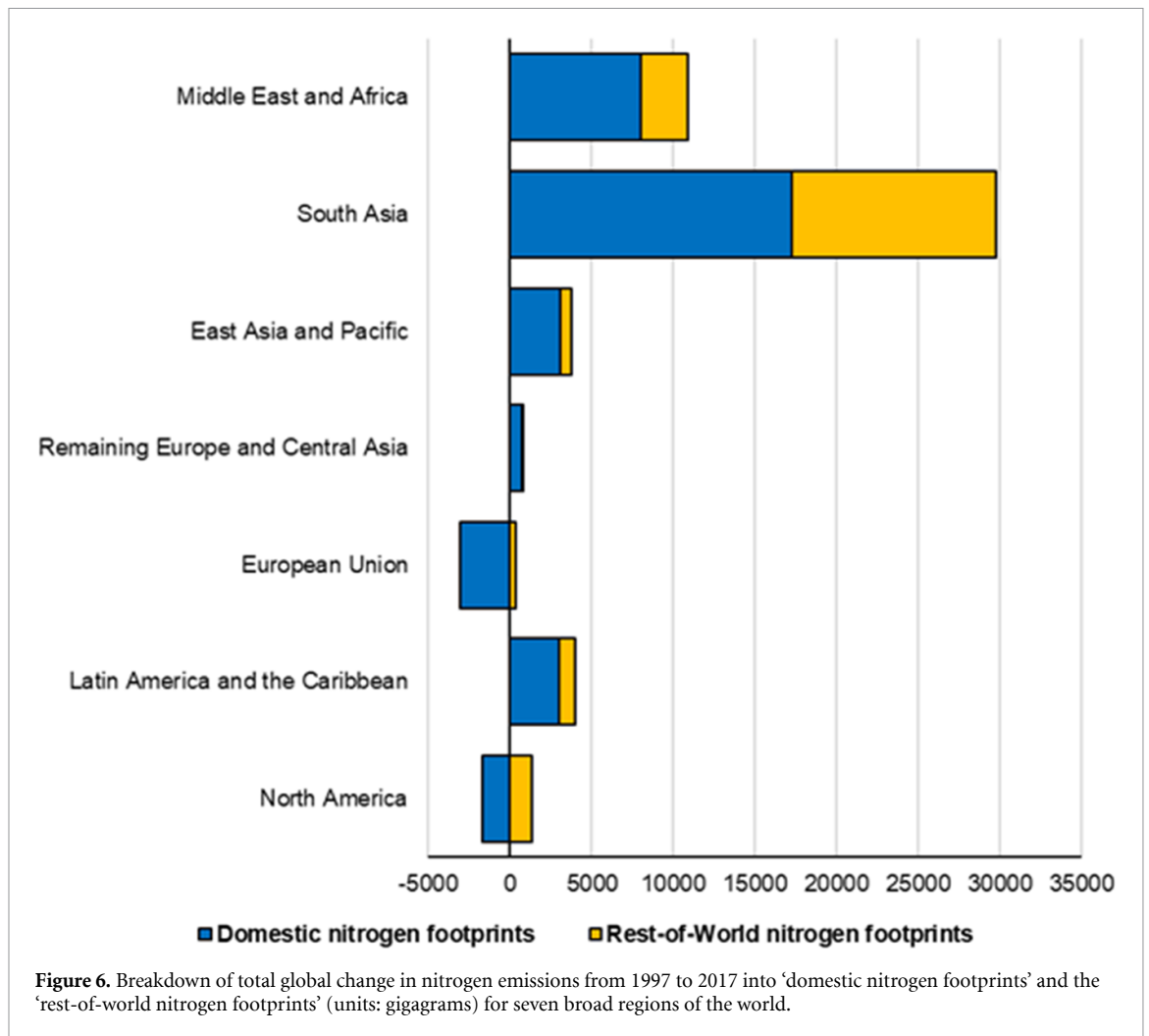
3.2.3. Production recipe and final demand

A change in production recipe refers to the substitution of inputs to produce goods and/or services. In essence, the change occurs due to the rearrangement of supply chains. Overall, Nr emissions have slightly increased as industries substitute existing inputs with alternatives. Interestingly, the overall reductions have resulted from the cancelling out of contributions from DFs and the RoWFs (see section 3.3). Changes in production recipe also take place when industries outsource nitrogen-intensive production to other nations. This concept is explained in detail in section 3.3.

Changes in the consumer baskets and final demand by destination effect (i.e. investment/consumption shifts) have resulted in a rise in emissions (figures 4 and 5). The commodity content of consumer baskets has largely shifted from vegetable-based products to livestock-based products such as meat, eggs and dairy foods (Kearney 2010). European countries, in particular, have experienced an increase in poultry consumption (Magdelaine *et al* 2008). Production of animal-source foods have been shown to be important for the economic development of Asia and Africa (Baltenweck *et al* 2020). Livestock production systems are one of the largest contributors of Nr emissions (Galloway *et al* 2010). International trade of meat and animal products can result in the transfer of these emissions across continents (Oita *et al* 2016). Likewise, urbanisation and trade liberalization have driven the development of processed food outlets around the world. These developments in turn have significant implications for human health, evident from a rise in obesity and cardiovascular disease (Thow and Hawkes 2009).

3.3. Regional dynamics

We calculate the change in emissions from 1997 to 2017 for seven broad global regions: *North America, Latin America and the Caribbean, European Union, Remaining Europe and Central Asia, East Asia and Pacific, South Asia, Middle East and Africa*. Then, we dissect the total nitrogen footprint for each region into contributions from their respective domestic economy (DF) and international trade (RoWF) (figure 6), and identify drivers thereof (table 1). We further select five typical economies to assess DF and RoWF trends at country-level and over four-year intervals, starting from 1997 (figure 7). DF refers to nitrogen emissions happening in a region for satisfying its own consumption, for example emissions taking place in Australia for satisfying domestic consumption by Australian residents (see figure 2). Conversely, Rest-of-the World footprint takes into



account emissions taking place outside of a country's borders (e.g. in Japan or USA) for satisfying a country's final consumption (e.g. consumption in Australia). Put simply, the DF includes emissions embodied within a country's domestic supply chains, whereas the RoWF includes all international supply chains outside of a country. This split allows for the investigation of the contribution of international trade in driving Nr emissions.

Interestingly, both the DF and the RoWF of South Asia have increased from 1997 to 2017, highlighting two key aspects: (a) economies of this region are key production hubs of nitrogen-intensive commodities that are used for domestic consumption, and for exports (i.e. high DF); and (b) economies of these regions significantly trade with each-other, resulting in high RoWF. 'Middle East and Africa' has also seen a rise in DF, with rising population growth and affluence outpacing improvements in technology (See SI 4). Noticeably, the DF of developed economies, such as North America and the European Union, has decreased over the analysed period, largely due to outsourcing of nitrogen-intensive production to South Asian economies. The phenomenon of outsourcing

has been documented for greenhouse gas emissions, especially carbon dioxide emissions (Malik and Lan 2016).

Overall, as documented in section 3.2, improvements in technology and nitrogen management practices have significantly decreased Nr emissions. Affluence and Population have continued to drive these emissions. An interesting observation can be made for changes in industrial structure ('Production recipe'), which have driven the RoW Nr emissions, but these rises have been counteracted by reductions in emissions pertaining to changes in production recipes from a domestic perspective (table 1, figure 7).

Analysis of emissions over short periods offers insights about the changing trends over various intervals (figure 7). Affluence has largely driven the increase in emissions, except for effects felt during economic depressions. Population growth has also contributed to emission fluxes around the globe, except for Germany in 2005–09 when the country experienced a slight decrease in population due to low birth-rates (Daley and Kulish 2013). Each economy has a specific characteristic that defines its production

Table 1. Breakdown of total global change in nitrogen emissions from 1997 to 2017 into ‘domestic nitrogen footprints’ and the ‘rest-of-world nitrogen footprints’ for seven broad regions of the world, and their drivers thereof.

		Nitrogen efficiency	Production recipe	Final demand composition	Final demand destination	Affluence	Population
Total nitrogen footprints	North America	−12 926	181	−39	48	8407	3949
	Latin America and the Caribbean	−7099	−586	−584	−535	8017	4779
	European Union	−17 228	1435	1517	−715	10 962	1325
	Remaining Europe and Central Asia	−14 852	2059	−98	32	12 949	728
	East Asia and Pacific	−20 048	4570	1407	−620	13 692	4773
	South Asia	−124 256	−9183	−2511	−6027	154 977	16 725
	Middle East and Africa	−18 590	3517	1641	1294	12 155	10 886
			Nitrogen efficiency	Production recipe	Final demand composition	Final demand destination	Affluence
Domestic nitrogen footprints	North America	−6665	−1265	−1408	29	5162	2422
	Latin America and the Caribbean	−4544	−1118	−1013	−408	6240	3828
	European Union	−7131	−1064	−815	−450	6027	366
	Remaining Europe and Central Asia	−10 473	1380	−235	51	9703	301
	East Asia and Pacific	−10 591	694	278	−662	10 280	3045
	South Asia	−117 008	−12 302	−3785	−5172	140 426	15 066
	Middle East and Africa	−14 176	2320	1754	1100	9063	7907
			Nitrogen efficiency	Production recipe	Final demand composition	Final demand destination	Affluence
Rest-of-world nitrogen footprints	North America	−6260	1446	1370	20	3245	1527
	Latin America and the Caribbean	−2555	533	429	−127	1778	952
	European Union	−10 096	2499	2332	−265	4935	959
	Remaining Europe and Central Asia	−4379	678	138	−19	3246	427
	East Asia and Pacific	−9457	3876	1130	42	3411	1728
	South Asia	−7248	3119	1274	−855	14 550	1659
	Middle East and Africa	−4414	1197	−113	194	3092	2979

structure and interactions with other regions and sectors. For example, India’s DF is much higher than its RoW footprint, since the country is one of the major exporters of agricultural and livestock products (Oita *et al* 2016).

Global regions can be further categorized into so-called ‘leaks’ and ‘sinks’ of Nr emissions, as analysed by Malik and Lan (2016) for the case of carbon dioxide emissions. We use the term ‘leaks’ to refer to countries with RoWF (due to imports) growing

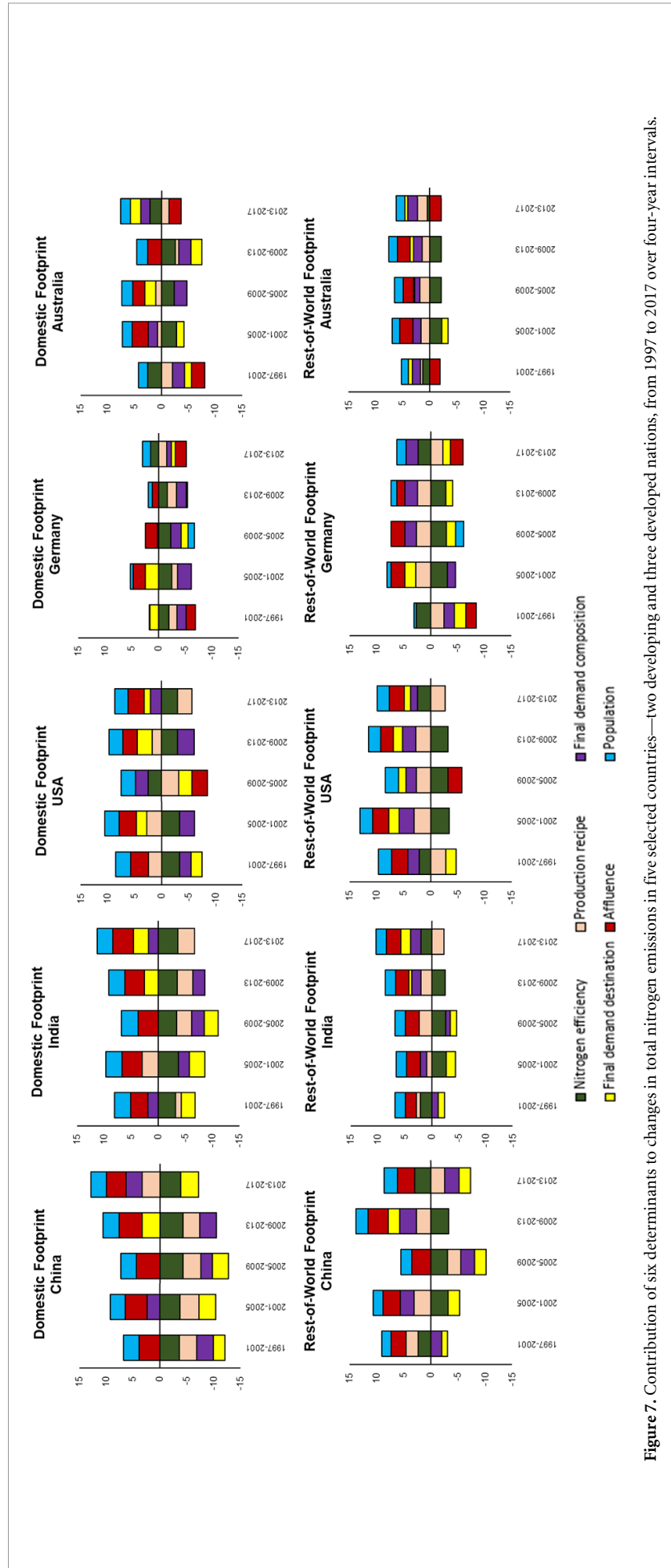


Figure 7. Contribution of six determinants to changes in total nitrogen emissions in five selected countries—two developing and three developed nations, from 1997 to 2017 over four-year intervals.

stronger than their DF; and we use the term ‘sinks’ to refer to countries with DF (due to exports) growing stronger than RoWF. Regions with a large RoWF in comparison to the DF, such as European Union, North America can be categorised under ‘leaks’, whilst those with a large DF, such as South Asia, Middle East and Africa can be considered as ‘sinks’. South Asia (featuring China and India) is a production hub of nitrogen-intensive commodities that are used domestically (hence high DF) and are exported (in other words, imported by other countries). South Asia is therefore regarded as a ‘sink’, because other countries import commodities from South Asia. Interestingly, South Asia also has a high RoWF as the countries falling within this aggregated category trade with each other. For example, China exported about 70 billion USD worth of commodities to India in 2019, from electronic items to machinery, chemicals, agricultural products and much more. In the same year, India’s exports to China were worth 17 billion USD, including 2 billion USD of petroleum oils (ATLAS 2021).

4. Policy implications

A nitrogen footprint enables the quantification of the total pressure on the environment by a consumption activity by considering the entire life-cycle of products. For the case of nitrogen, the supply chains of food products are especially important, since nitrogen is directly used for the production of crops (Lassaletta *et al* 2014, Erisman *et al* 2018). The agri-food supply chain includes many actors—from the fertilizer industry to farmers to wholesalers/retailers and finally consumers. At every step in the chain there are either nitrogen losses (e.g. on farms) or overconsumption (e.g. excessive application of nitrogen fertilisers or excessive unsustainable consumption and food wastage). Such complex interconnected network of actors and their impact on the nitrogen cycle warrants the need for implementation of policies at not just farm-level, but from farm to fork. In particular, as this study shows, there are three key drivers of nitrogen emissions—efficiency (negative effect), affluence (positive effect) and population growth (positive effect).

Increasing nitrogen efficiency at the farm-level involves implementation of soil and plant management practices (Yadav *et al* 2017), which enhance nitrogen efficiency, in turn positively impacting environmental quality. Efforts to implement effective nitrogen-management practices have been around since mid-1900s, as governments around the globe started to recognize the damaging effects of nitrogen to air, water and soil quality, and human health. Early work in implementing legislation for improving nitrogen management practices was undertaken in the developed world. For example, in the USA, efforts to pass legislation for protecting the environment

started with the Federal Water Pollution Control Act in 1948, followed by the Air Pollution Control Act in 1955, the Clean Air Act in 1963, the Safe Drinking Water Act in 1974, the Clean Water Act in 1977, and the Harmful Algal Bloom and Hypoxia Research and Control Act in 1998. In Europe, the Soil Protection Act in 1971 aimed at reducing over-fertilisation in the Netherlands was one of the first acts to be implemented in the continent (Velthof *et al* 2012, Winiwarter *et al* 2015), followed by the first Convention on the Protection of the Marine Environment of the Baltic Sea signed in 1974, the United Nations Economic Commission for Europe Convention on Long-range Trans-boundary Air Pollution signed in 1979, the European Union’s Urban Waste Water Directive issued in 1991, the Nitrates Directive adopted by the European Commission in 1991, and the Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic signed in 1992 (Sutton *et al* 2013). Developing countries, such as India, have been working on implementing new methods, such as slow- and controlled-release fertilizers, site-specific nitrogen management by using in-season diagnostic tools, efficient water management and decision-support systems (Patra 2018). These support systems are now starting to be used in African nations (Tsujimoto *et al* 2019).

Globally, there have been more than 2700 policies implemented to address nitrogen pollution at various scales (local and national) (Kanter *et al* 2020a), with 971 in Europe, 610 in Asia, 384 in North America, 364 in Africa, 299 in South America and 90 in Oceania (*categorization based on the authors*). Efforts are also underway by the United Nations Environmental Program Nitrogen Working Group to establish an inter-convention nitrogen coordination mechanism (Sutton *et al* 2021).

Whilst a considerable amount of attention is given to nitrogen management at the production-level, not much has been done about overconsumption at a consumer level. A lack of policies aimed at consumers highlight the challenges in regulating their behaviour and consumption choices. Kanter *et al* (2020b) present some government policy interventions at a consumer-level, which can indirectly positively influence decision-making at the production-level, e.g. increasing education of food waste, composting, dietary choices for consumers to make informed decisions, implementing taxes on foods containing high nitrogen footprint, and implementing standards for low-nitrogen footprint food options in schools and cafes.

5. Conclusions

In this study we examined the drivers of a change in Nr emissions for four key Nr species—nitrogen oxides (NO_x), nitrous oxides (N₂O), ammonia (NH₃) and nitrogen exportable to water bodies (NO₃⁻).

Our results show that whilst nitrogen efficiency has somewhat decelerated the growth in emissions, the combined effect of affluence, population growth and changes in final demand have outpaced any reductions. Furthermore, trade liberalization and globalization have narrowed the gap between production hotspots of Nr release and consumption sites. We find that South Asia has a high DF and RoWE, which means that South Asia not only exports nitrogen-intensive commodities to other countries, but also trades domestically (i.e. countries in South Asia actively engage in trade of goods). The developed world mostly acts as the nitrogen-leaking region (as in the countries in this region import nitrogen-intensive goods from developing regions, such as South Asia, Middle East and Africa). Our results highlight the need to devise policy measures for further enhancing nitrogen efficiency for effectively mitigating the effects of Nr, not just at a producer-level but also consumer-level, and for judicious use of nitrogen fertilisers on crops.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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