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Title: A framework for nitrogen futures in the shared socioeconomic pathways

Abstract

Humanity's transformation of the nitrogen cycle has major consequences for ecosystems, climate and human health, making it one of the key environmental issues of our time. Understanding how trends could evolve over the course of the 21st century is crucial for scientists and decision-makers from local to global scales. Scenario analysis is the primary tool for doing so, and has been applied across all major environmental issues, including nitrogen pollution. However, to date most scenario efforts addressing nitrogen flows have either taken a narrow approach, focusing on a singular impact or sector, or have not been integrated within a broader scenario framework – a missed opportunity given the multiple environmental and socio-economic impacts that nitrogen pollution exacerbates. Capitalizing on our expanding knowledge of nitrogen flows, this study introduces a framework for new nitrogen-focused narratives based on the widely used Shared Socioeconomic Pathways that include all the major nitrogen-polluting sectors (agriculture, industry, transport and wastewater). These new narratives are the first to integrate the influence of climate and other environmental pollution control policies, while also incorporating explicit nitrogen-control measures. The next step is for them to be used as model inputs to evaluate the impact of different nitrogen production, consumption and loss trajectories, and thus advance understanding of how to address environmental impacts while simultaneously meeting key development goals. This effort is an important step in assessing how humanity can return to the planetary boundary of this essential element over the coming century.

Keywords: Scenarios; Nitrogen Pollution; Environmental Policy

Highlights

- Nitrogen pollution is a critical environmental issue
- Scoping the range of possible future nitrogen flows is crucial
- New nitrogen narratives are presented based on the Shared Socioeconomic Pathways
- They can help to understand how to achieve both environment and development goals

1) Introduction

Nitrogen (N) pollution is one of the most important environmental issues of the 21st century (Sutton et al., 2019). N and phosphorus (P) flows are one of only two planetary boundaries – a level of human interference with the environment beyond which damage increases dramatically and possibly irreversibly – that recent studies suggest humanity has exceeded due to the immense increase in global food, feed and fiber production since the mid-20th century (Steffen et al., 2015, Springmann et al., 2018). The impacts of N lost to the environment range from local (soil health and water pollution) and regional (air pollution and biodiversity loss) to global scales (climate change and stratospheric ozone depletion). In economic terms, N pollution is estimated to cost the global economy 200-2000 USD billion annually, equivalent to 0.2%-2% of global GDP (Sutton et al., 2013). Today, more than half of the global N cycle is driven by anthropogenic sources, namely the Haber-Bosch process, fossil fuel combustion and agricultural biological N fixation (Galloway et al., 2008, Fowler et al., 2015).

Looking ahead, anthropogenic amplification of the N cycle is expected to grow, with global food demand anticipated to increase 60% by 2050 from 2005 levels (Alexandratos and Bruinsma, 2012). This, together with ambitious climate mitigation measures requiring significant amounts of land, such as bioenergy and afforestation, could stimulate further agricultural intensification with important implications for N use (Popp et al., 2011, Humpenoder et al., 2018). Climate policies and population trends will also influence future N pollution from non-agricultural sources such as fossil fuels and wastewater (Rao et al., 2017, van Puijenbroek et al., 2019). It is thus crucial to provide scientists, policymakers and other key stakeholders a sense of how local to global-scale N pollution trends could progress over the coming decades, and what the potential effects of N management measures and policies could be.

A widely used methodology in assessing global environmental challenges is the use of storylines that qualitatively describe how different futures may unfold, and derivative scenarios for subsequent quantitative analyses. We define a scenario as a set of quantitative inputs and assumptions that represent a vision of a specific future, which can then be used by models to simulate outcomes (van Vuuren et al., 2012). A collection of scenarios set over a common time horizon can therefore provide a range of possible futures for a particular issue. They can then be used for decision-support and as markers for measuring progress towards a desirable future. This approach has been used across a range of environmental issues, including climate change and biodiversity loss (van Vuuren et al., 2011b, MEA, 2015).

N has been part of several past environmental scenario exercises given its central role in key biological and environmental processes (Section 2). However, N has rarely been the sole and explicit focus of global environmental outlooks. Scenario efforts addressing N flows to date have generally taken a narrow approach, focusing on a singular impact or sector such as air pollution or agriculture (Bodirsky et al., 2014, van Vuuren et al., 2011a). Dedicated N scenarios evaluating future N flows and the impact of targeted interventions to reduce N pollution have not been integrated within broader environmental scenario frameworks. This is a significant gap given the multiple environmental and socio-economic impacts that nitrogen pollution exacerbates (Galloway et al., 2003, OECD, 2018). In the absence of a single source that combines all available knowledge on future N trends and links these to a consistent set of policy options, the scope of future N flows cannot be adequately addressed by decision-makers and other stakeholders.

The Shared Socioeconomic Pathways (SSPs) is one of the most important and widely applied environmental scenario frameworks to emerge in recent years – a set of five storylines describing a range of societal trajectories defined by socio-economic, demographic, technological, lifestyle, policy, institutional and other drivers (Riahi et al., 2017). Combined with the four Representative Concentration Pathways (RCPs) which span a range of radiative forcing futures and thus greenhouse gas emissions trajectories (Moss et al., 2010), they form the backbone of the climate projections used in Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (IPCC, 2014) and the recent IPCC Special Report on 1.5 degrees (Frieler et al., 2017). The broad basis of the SSP framework also enables their application across a range of other environmental issues including air pollution, ecosystem services, land-use and water (Mouratiadou et al., 2016, Popp et al., 2017, Kim et al., 2018, Mogollon et al., 2018, Rao et al., 2017, van Puijenbroek et al., 2019).

This paper presents a new set of N narratives within the SSP framework, as part of a new project launched in 2017 by the United Nations Environment Program with funding through the Global Environment Facility, entitled Towards an International Nitrogen Management System (INMS). This new science-policy initiative is focused on targeted research for improving understanding of the nitrogen cycle and aims to produce the first International Nitrogen Assessment by 2022, including benchmarking contemporary conditions and evaluating potential future scenarios via a set of modeling tools. The SSPs enable such an analysis because of their broad use across environmental science, their internal consistency across economic, social and environmental dimensions, and their lack of prescriptive policy elements, allowing for the integration and analysis of new measures. For the purposes of this study, the SSPs and RCPs generate a range of baseline trends and N relevant-drivers out to 2100, which provide the foundation for specific N policy interventions differentiated by ambition level to represent a broad spectrum of possible N futures (Figure 1). A follow-up paper will implement and evaluate these storylines and scenarios using a suite of integrated assessment models (IAMs) as part of the next stage of the INMS project.

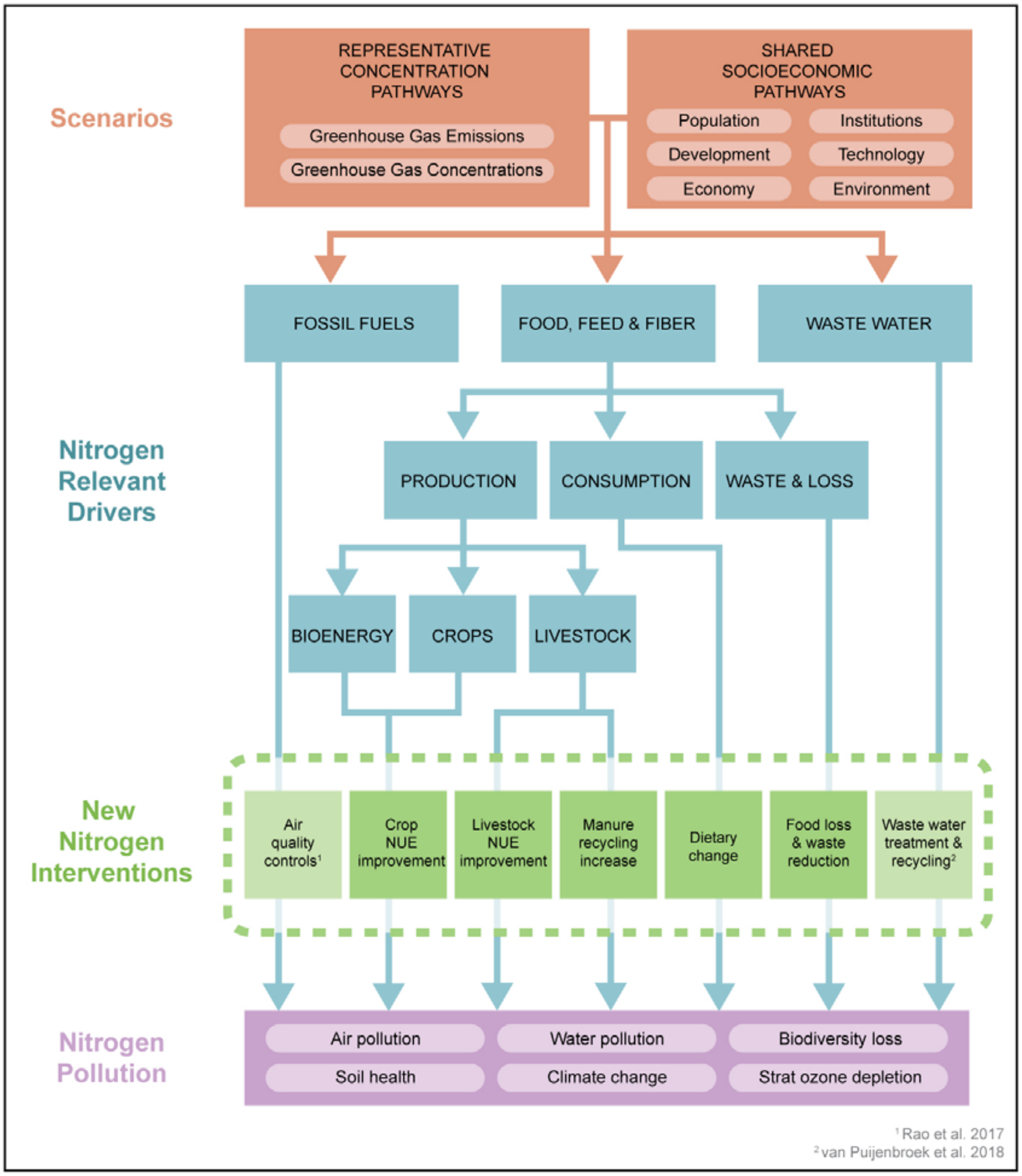

Figure 1: The integration of new nitrogen (N) interventions within the Shared Socioeconomic Pathway (SSP)/Representative Concentration pathway (RCP) framework. The SSP/RCP combinations generate estimates of N-relevant drivers such as food, feed and fiber production, consumption, waste and loss. In order to provide models with a full range of possible N futures to evaluate, this paper introduces a number of new N interventions across the food system combined with previously published interventions to address air quality and wastewater for models to implement. The light green boxes in in the “New Nitrogen interventions” section refer to previously published nitrogen trajectories within the SSP literature. “NUE” refers to nitrogen use efficiency - the ratio of farm-level N outputs to N inputs. The purple N pollution outcomes would result from the model implementation of these new narratives.

We first evaluate past scenario efforts to address N flows (Section 2). We then define indicators and ambition levels for a suite of N policy interventions differentiated by development status (Section 3). Next, we describe a tiered scenario protocol organized around a subset of scenarios for modeling groups to prioritize (Section 4) and conclude with a discussion of ways forward (Section 5). This paper contributes to the growing literature using the SSPs to provide researchers and policymakers a framework for evaluating a consistent set of environmental futures based on key drivers of change. Our new N narratives can be used to explore environmental futures, with the aim of advancing understanding of solutions to global environmental problems and enabling informed and effective decision-making across scales.

2) Past scenario efforts from a nitrogen perspective

Environmental scenario development has a rich history (Wiebe et al., 2018), though N production, consumption and loss has seldom been a central focus. The IPCC Special Report on Emissions Scenarios (SRES) published four storylines based on the degree of globalization versus regionalization and the priority given to economic versus social and environmental objectives (Nakicenovic, 2000). N was not a priority, with only N_2O and NO_x emission projections included because of its focus on climate and air quality (Davidson and Kanter, 2014). This narrow focus was repeated in the successors to the SRES scenarios, the RCPs (van Vuuren et al., 2011b). Meanwhile, global environmental change scenarios such as for the Millennium Ecosystem Assessment (MEA) took a broader perspective to study future atmospheric (NH_3, N_2O and NO_x) and riverine N losses based on changes in N fertilizer and manure, driven by changes in population and food demand (Mayorga et al., 2010, Seitzinger et al., 2010, van Vuuren et al., 2011b, Bouwman et al., 2013a, Bodirsky et al., 2012, Bouwman et al., 2009). Nevertheless, the focus on N use, production and losses was limited towards its effects on the provision of ecosystem services.

The emergence of N as an increasingly important environmental issue led to new scenarios devoted solely to N – both sector- and compound-specific, as well as for total N. An UN

Environment Program assessment of N_2O found that emissions equivalent to 60 Gt CO_2 could be avoided with ambitious mitigation by 2050 – equivalent to 5%-10% of the remaining carbon budget consistent with a 2 °C world (UNEP, 2013, Kanter, 2018). Recent studies have focused on the agricultural sector, given its dominance as a source of N pollution, with scenarios based on projected changes in crop demand, agronomic improvements and environmental impacts such as climate change (Bouwman et al., 2013b, Bodirsky et al., 2014, Zhang et al., 2015). Several scenario-based studies assess global totals of reactive N flows as one form of reactive N can be transformed into another with relative ease (Galloway et al., 2008, Fowler et al., 2015, Erisman et al., 2008, Winiwarter et al., 2013). However, these scenarios are rarely comprehensive in scope, tending to focus on either one specific impact or polluting sector. Or if more holistic, they do not evaluate policy interventions specifically devoted to better managing N flows.

This is critical because returning to the planetary boundary for N will require large-scale and cross-sectoral changes in food consumption, agricultural production and land use, as well as in transport, industry, and wastewater management (Springmann et al., 2018, Bodirsky et al., 2014, de Vries et al., 2013). These changes require interventions explicit to N that take into account the interactions with other social and environmental issues such as food security and climate change in a way that recognizes the N imbalances across the globe. The SSPs provide such a holistic framework.

3. Recent developments in N-relevant SSPs

The SSPs were initially created to provide socio-economic storylines that describe a number of challenges for reaching different climate adaptation and forcing levels by 2100. Each of the five SSPs is defined by different trajectories in major socioeconomic, demographic, technological, lifestyle, policy, institutional and other trends. They encompass a range of futures that span the societal challenges associated with mitigating and adapting to climate change (Riahi et al., 2017). The SSP storylines have been translated into quantitative form by a suite of Integrated Assessment Models (IAMs). What makes SSPs interesting from an N perspective is that recent studies have used them as an overarching framework for developing new and complementary scenarios for N-relevant environmental issues such air pollution (Rao et al., 2017), land use change (Popp et al., 2017), energy (Bauer et al., 2017), and wastewater management (van Puijenbroek et al., 2019). This section synthesizes previous N-relevant work using the SSP framework and discusses their relevance to the new narratives presented in Section 4.

Mogollón et al. (2018) recently projected future agricultural N inputs and N use efficiency (NUE) for global croplands across the five SSPs using the IMAGE model, with N fertilizer use in 2050 ranging from 85 Tg N yr^{-1} in SSP 1 and 260 Tg N yr^{-1} in SSP 5 (Mogollon et al., 2018). NUE trajectories are split into four categories, based on previous work by Lassaletta et al. (2014): Type 1 countries display NUE decreases due to increasing N use without a concomitant increase in yields; Type 2 and 3 countries display steady increases in NUE due to either increases in yield and/or declines in N application rate; and Type 4 countries show increasing NUE in low N environments, most likely due to N mining (Lassaletta et al., 2014). Our approach extends this work by providing explicit N policy narratives to evaluate the impact of mitigation targets across all major N-polluting sectors, including livestock production, industry, transport and wastewater treatment.

Other issue-specific SSP papers have N-relevant aspects that we integrate within our broader set of N narratives (Table 1). For N impacts on air quality, Rao et al. (2017) created three air pollution narratives representing high, central and low pollution control ambitions out to 2100 (Rao et al., 2017). These narratives are differentiated by pollution targets embedded in current legislation in OECD countries, the speed at which developing countries "catch up" with OECD countries on air quality policy, and the pace of change at the technology frontier. Based on regional emission factors and simulated activity levels, IAMs produced scenario-specific estimates for future ammonia (NH_3) and nitrogen oxides (NO_x) emissions – N compounds that are also key air pollutants – from transport, industry, fossil fuel combustion and agricultural waste burning.

The SSP land-use narratives are differentiated by level of land-use regulation, agricultural productivity, dietary preferences, trade patterns, globalization and climate mitigation approaches, with important implications for agricultural N_2O emissions (Popp et al., 2017).

For example, SSP 1 is characterized by strong land-use regulation, with tropical deforestation rates significantly reduced, increasing crop yields, lower animal-calorie diets and low food waste, with strong international cooperation on climate change – representing the lower bound of agricultural N_2O emissions by 2100. By contrast, in SSP 3 land-use change is barely regulated, with crop yield increase strongly diminished due to very limited transfer of new agricultural technologies to developing countries. This is compounded by a relatively high share of animal-calorie in diets and food waste, with little international cooperation on climate change – representing the upper bound of agricultural N_2O emissions by 2100. Superimposing the RCPs onto these SSP land-use narratives subsequently demonstrates how bioenergy production, animal consumption and greenhouse gas emissions under different climate scenarios can impact N consumption, production and pollution trends.

Finally, van Puijenbroek et al. (2018) uses the SSP framework to build narratives about future nutrient losses to urban wastewater and wastewater recycling in the agricultural sector (van Puijenbroek et al., 2019). By 2050, outcomes range from four (SSP 1 and SSP 5) to eight (SSP 3) billion people not connected to a sewage system with nutrient concentrations in wastewater projected to increase by 30% (SSP 5) to 70% (SSP 3), largely in the developing world. Nutrient collection could be a significant component of new sewage systems (SSP1 and SSP 5), potentially allowing for large amounts of recycled N to be used as an agricultural input (Magid et al., 2006).

The existing work described here is combined with new and explicit N measures on food, feed and fiber production, consumption, waste and loss described in the following section to create a set of consistent and comprehensive N narratives within the SSP framework (Table 1).

4. New nitrogen narratives within the SSPs

The multi-impact and multi-scalar nature of N pollution has major governance challenges and implications for the scope of new N narratives (Kanter, 2018). The planetary boundary for N is based on several different environmental thresholds for agricultural N losses – from atmospheric NH_3 concentrations for air quality, N concentrations in surface water for water quality, to radiative forcing from N_2O for climate change (de Vries et al., 2013). A singular focus on reaching any one threshold would lead to different N mitigation targets and increase the potential for pollution swapping between N compounds given how highly interconnected the N cycle is (Galloway et al., 2003). Consequently, this study adopts a more integrated yet regionally distinct approach to N pollution narratives that acknowledges the heterogeneity of N consumption patterns across the world and focuses on using N as a resource more efficiently as opposed to addressing specific environmental impacts in an isolated manner. Nevertheless, such an approach will only evaluate how close each narrative comes to achieving the N planetary boundary *ex post*.

4.1 Indicators

The first step to integrating N-focused narratives within the SSPs is the identification of specific indicators to measure progress, particularly in the agricultural sector given its dominant role in N consumption, production and loss. Despite N's importance to multiple Sustainable Development Goals (SDGs), no N-specific indicator has been formally adopted to evaluate progress (Kanter et al., 2016). The chosen indicators are listed in Table 1.

For crop production we adopt the popular metric of N use efficiency (NUE) – the ratio of N in harvested crop biomass to total N inputs from synthetic fertilizers, manure, biological fixation and atmospheric deposition. Globally, crop NUE is approximately 40% on average, while a level close to 70% is estimated to be necessary to produce enough food to satisfy demand while returning to the planetary boundary for N (Zhang et al., 2015). Cropland NUE is improved by reducing N surpluses at the field scale – a strategy that can be implemented via the adoption of best management practices, such as multiple N applications throughout the growing season, GPS technology and soil N testing; and the use of enhanced efficiency fertilizers, which delay the release of N in the soil (Winiwarter et al., 2018).

For livestock production, we use manure excretion per unit animal product (kg N excreted per ton meat, milk or eggs) and manure recycling rates. We define the latter as the percentage of excreted N that is collected, stored and returned to agricultural land (i.e. either cropland or pasture). Globally, approximately half of livestock production is on grazing systems, with the other half in confined housing systems. While much of the total N excreted in grazing systems is directly returned to agricultural land, it is left unmanaged. And less than half of the N excreted in confined housing systems is collected, properly stored, recycled, meaning that global manure recycling rates range from 15%-25% across all forms of livestock production (UNEP, 2013). A more detailed regional breakdown of manure recycling rates can be found in Herrero et al. 2013 (Herrero et al., 2013). Increasing these rates requires improved manure capture, storage, treatment and utilization, while livestock excretion rates can be reduced via targeted improvements in animal breeding, feed quality and management, animal health, and herd management (UNEP, 2013).

For food losses and waste we use percentage of total food production not consumed by humans. Finally, for dietary change we use share of animal protein to total protein consumed (Springmann et al., 2018, Westhoek et al., 2015).

4.2 Policy ambition levels

Following the approach of Rao et al. (2017) we develop three N policy ambition levels representing high, medium and low pollution control outcomes, based on stakeholder perspectives and previously published evaluations of N management strategies. High ambition represents the frontier of technical feasibility in a timeframe largely consistent with the Sustainable Development Goals, which run until 2030. Moderate ambition reaches the same frontier over a longer time horizon (2050 or 2070), while low ambition represents either no improvement or a continuation of current trends, which can be negative (e.g. decreasing NUE). Given country differences in economic and agronomic circumstances, we create three country groups defined by their economic wellbeing and N use intensity, with three corresponding sets of N policy trajectories: OECD countries, non-OECD countries with moderate to high N use (defined as an N surplus greater than 50 kg N ha^{-1}, e.g. China), and non-OECD countries with low N use (N surplus less than 50 kg N ha^{-1}, e.g. Malawi), based on data from Zhang et al. 2015 (Zhang et al., 2015).

For crop production, the high and medium N policy ambition levels represent different years in which national-level NUE targets are reached. These NUE targets are taken from Zhang et al. (2015), which aim to keep 2050 crop N surpluses within the planetary boundary for N estimated by Bodirsky et al. (2014) (Bodirsky et al., 2014, Zhang et al., 2015). The low N policy ambition level represents a failure to meet these NUE targets at any point in the future, and a possible decrease depending on the country's economic group. For OECD countries, high N policy ambition assumes reaching target NUE by 2030 (and maintaining it until 2100), in line with the United Nations Sustainable Development Goals, whose success depends partially on future trends in N use (Kanter et al., 2016). Medium N policy ambition assumes meeting the same target NUE values, but 20 years later in 2050. Low N policy ambition assumes current NUE levels will remain constant out to 2100.

For non-OECD countries with moderate to high N use, the timeline for achieving target NUE begins from the time they become high-income countries (for 2010 this threshold was 12,275USD/capita/yr according to World Bank data). Achieving this represents having "caught up" with OECD countries. High N policy ambition assumes they reach target NUE in 10 years after catching up, while medium N policy ambition assume it takes 30 years. Low N policy ambition assumes NUE trends to improve along current trends, or to remain constant in case there are no evident improvements recently. Finally for non-OECD countries with low N use, high N policy ambition assumes they avoid the historically polluting N trajectories of other countries (from low input/high NUE to high input/low NUE and finally moderate input/high NUE) once they "catch up" with OECD countries and "tunnel through" from low input/high NUE to moderate input/high NUE over a 30-year period (Zhang et al., 2015). Moderate N policy ambition assumes these countries follow historical N trajectories over a 30-year period towards high input-low NUE before improving, while low N policy ambition assumes little improvement in current conditions, with sustained high NUE in the case of soil N mining and decreasing NUE in the case of increasing N application rates (Hutton et al., 2017). We assume that countries with decreasing NUE trends stabilize by 2030 at the latest in a low N policy ambition world. 2030 is the target year for the SDGs and when most countries' NUE will have reached the lowest measured bounds if current trends continue (Zhang et al., 2015). Table 1 provides a qualitative summary of these N policy ambition levels.

For livestock production, we adopt estimates and assumptions from the UNEP (2013) special report on N_2O (UNEP, 2013). Under high ambition policies, OECD countries reduce excretion rates by up to 30% by 2050 (2070 for moderate ambition) and achieve 90% manure recycling by 2030 (2050 for moderate ambition) – with the exception of countries like the US, Canada and Australia where livestock and crop production are not well integrated or proximate and which therefore have a different target of doubling recycling rates by 2050 (2070 for moderate ambition). Non-OECD/high N countries achieve the same excretion rate reductions ten years after becoming high-income countries (30 years for moderate ambition), while increasing recycling by 100% by 2050 (2070 for moderate ambition). Non-OECD/low N countries reduce excretion rates by 30% for new livestock production after 2030, with a 90% manure recycling rate by 2030 (2050 for moderate ambition). Current trends continue or remain constant under a low ambition scenario.

This study considers barriers to the adoption of N best management practices and mitigation technologies by farmers only insofar as different education trajectories are integrated into the SSP storylines (using illiteracy shares as a proxy) (Riahi et al., 2017). However, any policy that aims to achieve medium to high N policy ambition levels needs to consider other barriers to adoption such as cost, lack of extension services and land tenure (Kanter et al., 2019).

For dietary change and food loss and waste, we go beyond the Popp et al. (2017) specifications to explore the maximum N loss reductions achievable. We consequently adopt the most ambitious projections from Springmann et al. (2018): that by 2050 food loss and waste is reduced by 75% from current levels, and that diets shift towards a flexitarian diet based on strict limits for red and white meat as well as dairy, and high minimum amounts of legumes, nuts and vegetables (Willett et al., 2019). Given that these transitions depend as much on changes in consumer behavior as they do on technical developments (e.g. better farm storage facilities), we apply the assumption of Springmann et al. (2018) that these targets and timelines apply equally across all countries. This scenario is not listed in Table 1, but is listed in Table 3 as part of the scenario protocol. While this aspect of N consumption and loss is important to explore, it should also be noted that dietary shifts could have far-reaching feedbacks on feed vs. food vs. energy land-use distributions across different SSPs. And while N losses from landfills are not explicitly considered here, food waste is an important source; consequently, reductions in food waste will reduce the amount of N going to landfills (Gu et al., 2013b).

This framework does not consider industrial N in either structural (part of materials for long-term use such as nylon) or non-structural (released within a year of formation, such as certain explosives and pesticides) forms (Galloway et al., 2014). This is for two reasons: (1) there is still very little information available on N from industrial sources; and (2) much of it is thought to be in "locked" forms because of its long service life, with relatively small proportions lost to the environment (Gu et al., 2013a). Nevertheless, this growing source of reactive N should be considered in future rounds of scenario development.

Sector & country group		N policy ambition levels: *High*	*Medium*	*Low*	Indicators
Crop (Zhang et al., 2015)	*OECD*	Target NUE by 2030	Target NUE by 2050	Current NUE remains constant	Crop NUE (%) N surplus (kg N ha^{-1})
	Non-OECD/High N	Target NUE in 10 years after catch-up with OECD countries	Target NUE in 30 years after catch-up with OECD countries	NUE trends from past 10 years continue if negative until 2030, otherwise NUE remains constant	
	Non-OECD/Low N	Target NUE in 30 years after catch-up by avoiding historical trajectory	NUE follows historical trajectory towards high N/low NUE over 30 years, before improving	Current decreasing NUE trends continue akin to countries with similar socioeconomic status	
Livestock manure excretion (UNEP, 2013)	*OECD*	10% reduction by 2030, 30% reduction by 2050	10% reduction by 2050, 30% reduction by 2070	Current rates remain constant to 2050	N excretion per unit animal (kg N/LSU/yr) N excretion per unit animal product (kg N/kg meat, milk, eggs)
	Non-OECD/High N	N excretion rates same as OECD in 10 years after catch-up	N excretion rates same as OECD in 30 years after catch-up	Current trends continue if negative until 2030, otherwise remain constant	
	Non-OECD/Low N	30% reduction for new livestock production after 2030	30% reduction for new livestock production after 2050	Current trends continue or remains constant	
Manure recycling (UNEP, 2013)	*OECD*	90% recycling by 2030	90% recycling by 2050	Current rates remain constant to 2050	Excreted manure collected, properly stored and recycled (%)
	Non-OECD/High N	50% increase in recycling by 2030; 100% increase by 2050, or until 90% recycling reached	50% increase in recycling by 2050; 100% increase by 2070, or until 90% recycling reached	Current trends continue if negative until 2030, otherwise remain constant	
	Non-OECD/Low N	90% recycling in new systems by 2030	90% recycling in new systems by 2050	Current trends continue or remain constant	
Air Pollution (Rao et al., 2017)	*OECD*	70% of technically feasible measures by 2030, all measures by 2050	Current legislation (CLE) by 2030, 70% of technically feasible in 2050 increasing to all measures by 2100	CLE reached by 2040, further improvements slow	NO_x emissions (t N yr^{-1}) NH_3 emissions (t N yr^{-1})
	Non-OECD/High-Med income	Same as OECD in 10 years after catch-up	Delayed catch-up with OECD (CLE achieved by 2050), 70% of technical feasible reductions achieved by 2100	CLE reached by 2040, further improvements slow	
	Non-OECD/Low income	CLE by 2030, OECD CLE by 2050, gradual improvement towards 70% technical feasible measures	OECD CLE achieved by 2100	CLE reached 2050, further improvements negligible	
Wastewater (van Puijenbroek et al., 2019)	*OECD*	>99% wastewater treated; 100% N and P recycling from new installations from 2020	>95% wastewater treated 100% N and P recycling from new installations from 2030	>90% wastewater treated	Tertiary treatment rate (%) Secondary treatment rate (%) Sludge recycling (%) Organic recycling (%)
	Non-OECD/High N	>80% wastewater treated; Recycling same as OECD in 10 years after catch-up	>70% wastewater treated Recycling same as OECD in 30 years after catch-up	>60% wastewater treated	
	Non-OECD/Low N	>70% wastewater treated	>50% wastewater treated	>30% wastewater treated	

Table 1: Narratives of N abatement by sector. N policy ambition levels range from high to low, the former reflecting the frontier of technical feasibility and the latter no improvement or a continuation of current trends. Countries are split into three groups based on economic wellbeing and N-use intensity. Different ambition level targets for livestock manure excretion, manure recycling, air pollution and wastewater are taken from previous published studies (UNEP, 2013, Rao et al., 2017, van Puijenbroek et al., 2019). Additional interventions on bioenergy and dietary change are described in Section 5 and listed in Table 3.

Table 2 compares the scope and focus of the new storylines presented here with several of the major N-relevant studies described in Sections 2 and 3. These new narratives are the first to focus exclusively on N pollution, cover all reactive N compounds and sectors, and tie in with other major environmental and socioeconomic issues via the SSPs.

	MEA (Bouwman et al., 2009)	**RCPs (van Vuuren et al., 2011b)**	**UNEP (UNEP, 2013)**	**Bodirsky et al. (Bodirsky et al., 2014)**	**Mogollon et al. (Mogollon et al., 2018)**	**This paper**
Issue focus	Biodiversity and ecosystem services	Climate change	Climate change and ozone depletion	Nitrogen pollution	Nitrogen pollution	Nitrogen pollution
Compounds covered	All reactive N	N_2O, NO_x	N_2O	All reactive N	All reactive N	All reactive N
Polluting sectors covered	All sectors	All sectors	All sectors	Agriculture	Agriculture	All sectors
Links to existing frameworks/concepts	None	None	RCPs; SRES	Planetary boundaries	SSPs	SSPs

Table 2. A comparison of notable published N-relevant storylines and scenarios with the approach taken by this paper, based on issue focus, the compounds accounted for, the polluting sectors covered, and the links with broader scenario frameworks or environmental concepts. The framework of N narratives introduced in this paper is the first to focus exclusively on N pollution, cover all reactive N compounds and sectors, and have an explicit link to the other major environmental and socioeconomic issues via the SSPs.

5) Scenario protocol

The new N narratives described in Section 4 can be combined with the SSPs and RCPs to create a large suite of N scenarios, covering all plausible N futures. In order to prioritize the modeling work for future N assessments, we select a subset of these scenarios which will enable future modeling work to evaluate how a variety of important factors, from climate change, to policy ambition and socio-economic development, could impact future N production, consumption and pollution levels. See Table 3 for qualitative descriptions of these scenarios and the central differences between them. Figure 2 visualizes the superimposition of N policy ambition levels onto these specific RCP/SSP combinations.

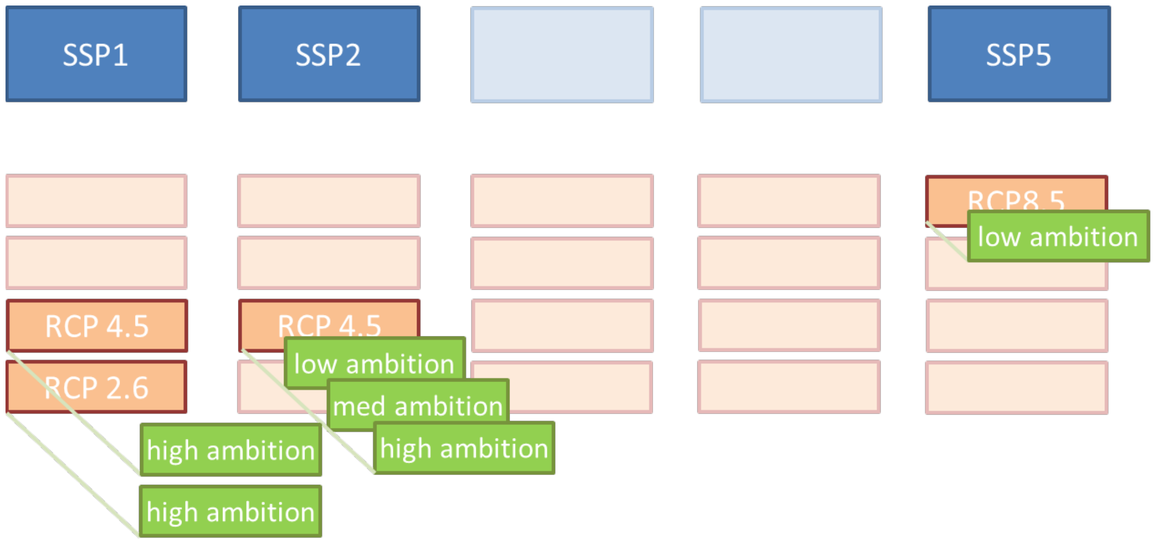

Figure 2: Scenario subset for modelers to prioritize to examine the impact of N policy ambition levels in the SSP/RCP scenario framework. SS1/RCP 4.5/High ambition vs. SSP 5/RCP 8.5/Low ambition represent the extremes of possible N futures, while the combination of SSP 2/RCP 4.5 with different N policy ambitions enables models to isolate the specific impacts of N interventions. The best-case scenario can be supplemented with high ambition dietary shifts (Table 2), while an optional bioenergy scenario allows for high ambition N mitigation to be evaluated in a high bioenergy world (SSP1/RCP 2.6.)

In order to capture the extreme ends of possible N futures, we selected two scenarios representing what we consider to be best- and business-as-usual outcomes for N pollution by 2100. The best-case is a low-N pollution scenario taken from SSP1 (Sustainability) in combination with RCP4.5 and high N policy ambition. In such a world, relatively ambitious climate action is coupled with a strong commitment to sustainable agriculture, with high productivity gains, low meat diets, and ambitious policies explicitly targeting N pollution and other environmental impacts from the land-use sector. While RCP 2.6 is the best-case climate scenario, we assume that unless serious efforts are made to improve NUE in bioenergy production (see below), RCP 2.6 would likely be worse from an N perspective than RCP 4.5. If possible within a specific model, a best-case “plus” scenario would include the high ambition dietary shifts and food loss and waste reductions described in Section 4.2. A combination of SSP 5 (“Fossil-fueled development”) with RCP8.5 and low N policy ambition most closely reflects a business-as-usual scenario. In this fossil-fuel-driven world, there is little to no climate action, high input-driven productivity threatened by climate impacts, meat-rich diets, and little to no policy explicitly targeting N pollution.

Then, in order to isolate the impact of different levels of N policy ambition, we select an intermediate scenario, SSP 2 combined with RCP 4.5, and impose the three N policy ambition levels onto it, generating an additional three scenarios. By keeping environmental and socio-economic trends constant, this trio of scenarios should help to isolate the impact that a focused approach to addressing N pollution (or not) could have on various sustainable development outcomes.

An optional seventh scenario combines SSP 1 and RCP 2.6 in order to evaluate the N challenges associated with bioenergy production, given its large anticipated contribution to energy production in a 1.5°C and 2°C world. While this SSP/RCP combination does not have the most dry matter production in 2100 from second-generation bioenergy crops according to Popp et al. 2017 (SSP 5/RCP 2.6 does), we believe that SSP 1 is the most likely storyline where NUE improvements in bioenergy production would be a policy priority. Previous research has shown that depending on the crop types used, and the total energy and land area required, bioenergy could be either a trivial or dominant source of N pollution and greenhouse gas emissions by 2100 (Davidson and Kanter, 2014). The recent IPCC Special Report on 1.5^{o}C suggests that a heavy reliance on bioenergy could substantially increase fertilizer use (Rogelj et al., 2018). For a best-case scenario, we would encourage modelers to apply the same NUE targets to bioenergy production as described for crops in Section 4.2.

Scenario	Climate	Development	Land-use	Diet	N policy
Business-as-usual	No mitigation (RCP 8.5)	Fossil-fuel driven (SSP 5)	Medium regulation; high productivity	Meat & dairy-rich	Low ambition
Low N regulation	Moderate mitigation (RCP 4.5)	Historical trends (SSP 2)	Medium regulation; medium productivity	Medium meat & dairy	Low ambition
Medium N regulation	Moderate mitigation (RCP 4.5)	Historical trends (SSP 2)	Medium regulation; medium productivity	Medium meat & dairy	Moderate ambition
High N regulation	Moderate mitigation (RCP 4.5)	Historical trends (SSP 2)	Medium regulation; medium productivity	Medium meat & dairy	High ambition
Best-case	Moderate mitigation (RCP 4.5)	Sustainable development (SSP 1)	Strong regulation; high productivity	Low meat & dairy	High ambition
Best-case +	Moderate mitigation (RCP 4.5)	Sustainable development (SSP 1)	Strong regulation; high productivity	Ambitious diet shift and food loss/waste reductions	High ambition
Bioenergy	High mitigation (RCP 2.6)	Sustainable development (SSP 1)	Strong regulation; high productivity	Low meat & dairy	High ambition

Table 2: Selected SSP-RCP-N scenario combinations for model evaluation

6) Conclusions

Better managing humanity's relationship with N is one of the most important challenges of our time, and clearly defined narratives for understanding how N trends may evolve over this century and impact other key environmental issues provide a crucial tool for researchers and decision-makers. The new N-focused narratives we present in this paper are based within the SSP framework which helps to link the emerging threat of N pollution with other relevant environmental issues. For example, cycles of nitrogen, carbon, and water are inextricably linked to each other and to societal pressures. Our narratives provide a consistent approach that can be used across scales and disciplines, toward creating novel framings for informed decision-making and developing solutions for N pollution problems. The next step is for these narratives to be used as inputs for modeling work interested in understanding humanity's impacts on the N cycle and the broader relevance of this essential element across society and the biosphere. As with the original SSPs and several of its offshoot studies, individual modeling teams will interpret and implement the narratives described in Table 1 differently, based on their model's strengths and weaknesses. The ultimate goal is for modeling work on this topic to share a set of common assumptions on future possible trajectories to facilitate model intercomparison and develop a common understanding of how nitrogen fluxes might evolve in the future.

A potential area for further narrative development is to evaluate the environmental impacts of a specific N policy target, for example halving N waste by 2050. This could give policymakers a clear sense of the environmental, agronomic and human health impacts of a precise and global policy goal, rather than scenarios that are the function of deeper underlying trends. The narratives presented here aim to reflect the range of possible N futures according to our current understanding, including the maximum potential for limiting N pollution while feeding a global population of 10 billion people. The environmental impacts of the technological and behavioral changes that underpin these narratives need to be explored using an array of models that are in line with the SSP storylines. Such work will reveal if it is possible to reduce N pollution within the planetary boundary and make progress towards the SDGs with the actions described here, or whether even more aggressive action is required. Advancing solutions to the N pollution challenge will require societal recognition of the importance of these issues and improved management of the N cycle.

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