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Towards a generic analytical framework for sustainable nitrogen management: application for China

Baojing Gu[1,2,*], Shu Kee Lam[2], Stefan Reis[3,4], Hans van Grinsven[5], Xiaotang Ju[6], Xiaoyuan Yan[7], Feng Zhou[8], Hongbin Liu[9] Zucong Cai[10], James N. Galloway[11], Clare Howard[3], Mark A Sutton[3], Deli Chen[2]

[1]Department of Land Management, Zhejiang University, Hangzhou 310058, PR China
[2]School of Agriculture and Food, The University of Melbourne, Victoria 3010, Australia
[3]NERC Centre for Ecology & Hydrology, Bush Estate, Penicuik, EH26 0QB, UK
[4]University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, UK
[5]PBL Netherlands Environmental Assessment Agency, PO BOX 30314, 2500 GH The Hague, The Netherlands
[6]College of Resources and Environmental Sciences, Key Laboratory of Plant-soil Interactions of MOE, China Agricultural University, Beijing 100193, China
[7]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, 210008, P.R. China
[8]Sino-France Institute of Earth Systems Science, Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, P.R. China
[9]Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[10]School of Geography Sciences, Nanjing Normal University, Nanjing 210097, China
[11]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22904, United States

***Corresponding Author:**
Department of Land Management, Zhejiang University, Zijingang Campus, 866 Yuhangtang Road, Hangzhou 310058, PR China. Tel & Fax: +86 571 8898 2615. E-mail: bjgu@zju.edu.cn

Abstract

Managing reactive nitrogen (N_r) to achieve a sustainable balance between production of food, feed and fibre, and environmental protection is a grand challenge in the context of an increasingly affluent society. Here, we propose a novel framework for national nitrogen (N) assessments enabling a more consistent comparison of the uses, losses and impacts of N_r between countries, and improvement of N_r management for sustainable development at national and regional scales. This framework includes four key components: national scale N budgets, validation of N fluxes, cost-benefit analysis and N_r management strategies. We identify four critical factors for N_r management to achieve the sustainable development goals: N use efficiency (NUE), N_r recycling ratio (e.g., ratio of livestock excretion applied to cropland), human dietary patterns and food waste ratio. This framework was partly adopted from the European Nitrogen Assessment and now is successfully applied to China, where it contributed to trigger policy interventions towards improvements for future sustainable use of N_r. We demonstrate how other countries can also benefit from the application our framework, in order to include sustainable N_r management under future challenges of growing population, hence contributing to the achievement of some key sustainable development goals (SDGs).

Key words: Cost-benefit analysis; Environmental protection; Food security; Nitrogen budget; Nitrogen use efficiency; Socioeconomic barriers; Sustainable development goals

Introduction

Human activities have more than tripled the global reactive nitrogen (N_r) creation rates and inputs to terrestrial ecosystems through industrial N fixation (Haber-Bosch process, HBNF), cultivated biological N fixation (CBNF) and unintended N oxide (NO_x) emissions from fossil fuel combustion, compared to the pre-industrial era [1]. The elevated N inputs to agriculture and forestry have substantially increased the supply of food, energy and materials, but also result in detrimental effects on the environment, human health, ecosystem structure and function, and climate [2, 3]. About 50% of the global population in the late-20th century was sustained by food production fertilized with N derived from the HBNF process [4]. However, more than half of the N used in agriculture is lost to the environment, largely as N_r [1, 5]. The same molecule of N_r can cause a sequence of effects and result in N cascading across multiple scales and environmental compartments [6], involving complex anthropogenic, biological, chemical, physical and geological processes [7] (Figure 1). A cost of 70-320 billion Euro have been attributed to detrimental effects on the environment and human health in Europe [8]. There is a substantial disparity in N use between global regions or countries, ranging from too much N use in Europe, the United States (US), India or China, to too little in Africa[9], impacting on the sustainability and food security in those regions. The regional differences in N use are determined by both human activities such as economic development [1, 5], and natural conditions such as climate and soil conditions [10, 11]. Understanding and managing the disparity in regional N uses and both their beneficial and adverse effects is crucial for global sustainable development.

Around the globe, substantial efforts have been made to understand and quantitatively assess the N cycles from the field to local/regional scales and the implication for food production and environmental protection[12]. The 7th international N conference held in Melbourne, Australia, in 2016 published the “Melbourne Declaration on Responsible Nitrogen Management for a Sustainable Future” (www.ini2016.com/melbourne-declaration) emphasising the need to conduct regional and global N studies to address the issues of N_r in food security, energy, health, environment, biodiversity and climate change around the world. The US, the European Union (EU) and India, have already completed comprehensive assessments of their N sources, fluxes, and impacts [7, 13, 14]. Some regions have implemented a series of policy measures to reduce N_r losses [15, 16]. However, specific findings and policies developed e.g. in the US and Europe may not be applicable to other regions, because the N challenges generally differ substantially between regions due to biogeochemical, socio-economical, cultural and political factors [5]. Other countries are conducting or intend to conduct N assessments to improve their N_r management, such as China [17]. Here, we propose a first comprehensive and uniform framework for the compilation of national N assessments, in order to better understand N cycling at national (or regional) scale, and to determine which policy can be developed and effectively implemented, as well as improving the transferability of this understanding and knowledge between regions and countries.

The framework and methodology for the national scale N assessment we have developed addresses several N related Sustainable Development Goals (www.undp.org/content/undp/en/home/sustainable-development-goals.html), in particular Zero Hunger (SDG2), Good Health and Well-Being (SDG3), Sustainable Cities and Communities (SDG11), Responsible Consumption and Production (SDG12), Climate Action (SDG13) and Life on Land (SDG16), while contributing to other SDGs and global objectives, e.g. the Convention on Biological Diversity (CBD). The framework includes four building blocks: (1) national N budget, (2) validation of N flux, (3) cost-benefit analysis, and (4) N_r management strategies. With these building blocks, a pathway for N_r sustainable management can be mapped out by integrating the socioeconomic factors and scientific understanding of the key processes of N cycling. With these approaches, N assessments in different countries can be compared on the same basis, contributing to a better understanding of regional N cycles, interactions across spatial scales, their driving forces and consequences. This will aid policy makers in formulating national policies towards sustainable N_r management in a wider regional context and in interaction with international communities, while considering international trade and cross-transboundary pollution, which exhibit increasingly important effects on global sustainability.

Key scientific questions addressed through N assessments

How are N uses and losses affected by natural and human factors? (Q1)

Unlike the globally uniform effects of a unit emission of a greenhouse gas on climate change [18], the environmental impact of a unit of N_r emission depends on the source, chemical form and location [8, 19]. Therefore, the environmental impacts of changes in N cycles are highly spatially explicit and thus mainly expressed at a regional or even local scale, and also with cross-boundary impacts [2]. Anthropogenic N inputs from different sources are generally well known, but the variation in their magnitude for some fluxes such as the biological N fixation (BNF) is still quite uncertain [1]. These uncertainties inevitably cascade through the N cycle on regional scale and result in multiple consequences, except for climate and ozone depletion impacts of N_2O emissions leading to effects on global scale [6].

Economic development increases fertilizer use through easier access to and reduced prices of fertilizer products, whereas improved management practices reduce N fertilizer use via increasing N use efficiency (NUE) [5]. NO_x emissions from fossil fuel combustion are directly related to energy consumption and technological development levels that control the emission rate during the combustion process [20]. NH_3 emissions show a strong temperature dependence, with more NH_3 emitted in warmer temperatures [21]. Generally, natural factors such as precipitation and temperature affect N cycling through changing N transformation rates and cycling pathways [11]. For instance, in dry regions more N losses through NH_3 emissions to the air occur, while transportation to groundwater and surface water is commonly found to be higher in humid regions [22].

Overall, regional variations of the N fluxes and their environmental impacts may be attributed to anthropogenic factors such as economic growth, technological advancement, policy innovation, and natural factors such as air temperature and precipitation [5] (Figure 2). These variations result in substantial uncertainties in N flows and fates [9]. Although recent studies have improved our understanding and hence the more accurate quantification of the global N flows and fates [1], uncertainties regarding N fluxes are still substantial due to inadequate understanding of N fates and their driving factors on a regional scale[17]. More regional work is needed to better understand the mechanisms and constrain the uncertainties.

How to quantify the societal costs and benefits of N uses? (Q2)

Quantifying the costs and benefits of N use is one way to address multiple, adverse as well as beneficial impacts of different chemical forms and sources of N_r (Figure 2). A consistent approach to the valuation of multiple impacts allows a weighted comparison of various uses (inputs) and emissions of N_r. Studies on the cost-benefit analysis of N cycles on a regional scale are scarce, and only selected studies[8, 19, 23] attempted a comprehensive assessment of costs and benefits in monetary terms. Large ranges and uncertainties exist in these previous estimates, e.g., the cost per kilogram of N_r loss ranges over one order of magnitude [8, 24]. The variation of population exposure to N_r pollutants in different regions might equally be a major cause of this large range [19]. Moreover, effects on ecosystem function and services are important, but typically not included [24, 25].

A substantial element of human health costs arising from atmospheric N_r pollution is the quantification of the loss of healthy life years due to exposure to fine (N-containing) particulate matter. NO_x contributing to the formation of tropospheric ozone and to a lesser extent, especially in urban areas, direct exposure to ambient concentrations of NO_2 also affects human health [8]. The societal cost of human health impacts depends on the statistical value attributed to a healthy life year, which is highly related to the income level of a country [26]. This illustrates that national assessments on the cost and benefit of N_r uses and losses are crucial, as they take into consideration national characteristics, such as population exposure rate and value of a healthy life year, and determine the most appropriate parameters for the analysis. To make the results from different countries comparable, a tiered approach is proposed to quantify the cost-benefit of N_r uses and losses. We distinguish five tiers that can be developed from criteria for environmental quality (Tier 1), to impacts of N_r pollution on ecosystems and health (Tier 2), nationally agreed policy objectives for environmental quality (Tier 3), metrics to aggregate impacts N_r on human health (e.g. Disability Adjusted of Life Years, DALY) and ecosystems (e.g. biodiversity or services) (Tier 4) and a loss or gain of prosperity or welfare in monetary terms (Tier 5). More details about the five tiers can be found in *SI text*.

What are the socioeconomic barriers constraining the more sustainable use of N? (Q3)

To mitigate N_r pollution, previous studies mainly focused on technological options, with little consideration of the context or the implementation costs of regulations [17]. For instance, the 4R approach (applying N fertilizer with the right type and right amount, at the right time and right location) has been recommended for many years in the US and EU [16], but has not been widely adopted in China owing to local constraints [27]. Excessive N fertilization is common in China, as a consequence of the average farm size being smaller than 0.1 hectare, which restricts the usage of advanced machineries, communication, information and training required for the implementation of the 4R approach [27]. Cui et al [28] engaged in training activities aiming to enable millions of smallholder farmers to implement advanced technologies; however, due to the high cost involved, it is difficult to maintain the skill levels after delivering training or extending such capabilities to a wider base of smallholder farmers [29]. Meanwhile, income from such small farms accounts for very little fraction of family income, reducing the incentive of better agronomic management practices. It implies that the socioeconomic barriers are sometimes critical for the sustainable use of N, even if technological or management approaches exist at zero or negative cost to the farmer. Meanwhile, the cost per unit of prevented N_r emission normally increases with cumulative emission reduction [8], suggesting it may be necessary to gradually adjust approaches to mitigate N_r pollution as more stringent emission controls and methods for N_r management are implemented. Hence, more work is needed to better understand the driving forces and barriers underlying these non-linear mitigation pathways. Also more work is needed on cost efficiency and cost-benefit analysis, including considering national and socio-economic characteristics (Figure 2).

Apart from the implementation costs of regulations, other barriers such as human behaviour related factors, e.g., culture, dietary preference, also affect the sustainable use of N [30] and opportunities to improve management. For instance, western diets (e.g., in the US) prefer beef over pork, while eastern diets (e.g., in China) prefer pork over beef. This implies that dietary structure regulations must consider the dietary culture in different countries to be effective. Policies or regulations developed in some countries may not transfer well to other countries due to the difference in socioeconomic barriers that constrain the sustainable use of N. Identifying and quantifying these barriers for the implementation of sustainable use of N_r through social surveys, sensitivity analyses and cost-benefit analyses on national scale, working with social science experts and economists in transdisciplinary contexts, can benefit a wider adoption of N regulation measures.

Methodology of the framework

Here, we introduce a hierarchical approach of how to conduct N assessments to achieve a sustainable and efficient use of N_r. The methodology broadly relates to the Driver–Pressure–State–Impact–Response (DPSIR) concept [31] (Figure 3). It comprises four stages (Figure 4). At the first stage, an integrated N budget is compiled using a mass balance model to analyse interactions between major components. All the sources, flows, losses, and the NUE in a country are quantified, including time series to reflect the past and current status and trends of N_r use. The first research questions (Q1), and the *Driver* and *Pressure* of the DPSIR concept are addressed at this stage (Figure 3).

At the second stage, data compiled from independent national field monitoring programs, remote sensing, and published data are used for comparison with those N fluxes obtained from the mass balance model from Stage 1 in order to validate model results. The results of the compiled N budget are total amounts of N fluxes, which differ from environmental quality objectives, i.e. N_r concentrations. Thus, a downscaling of national N fluxes to match with data from environmental quality monitoring at an appropriate, comparable scale is needed. The Pressure and State of the DPSIR concept will be addressed at this stage (Figure 3).

At the third stage, a cost-benefit analysis is applied to estimate both the costs and benefits of N_r use on ecosystems, human health and economy, considering the excess and accumulation, respectively the deficiency of N_r in the environment. The second key research question (Q2) and the *State* and *Impact* of the DPSIR concept are addressed at this stage.

At the final (fourth) stage, the results from the first three stages are integrated to assess how to build a sustainable future through improved N_r management (e.g., measures to maximize the benefits while minimizing the costs and damages of N_r uses) embedded in policies, institutions and regulations. The potential pathways to ensure an effective implementation of these regulations to overcome the socioeconomic barriers are also discussed. The last research question (Q3), and the *Response* of the DPSIR concept are addressed at this stage.

N budget modelling

To understand the changes of N fluxes, several datasets from both national statistics and global databases such as the Food and Agriculture Organization (FAO)[32]and International Fertilizer Industry Association (IFA) [33] can be accessed and compiled for analysis. Two types of data should be taken into account: human activities and N cycling parameters (e.g., NH_3 emission, runoff, and denitrification) (Figure 4). The datasets of human activities cover historical changes of population, urbanisation, production (industrial, crop, livestock and aquaculture), consumption (food, non-food goods, energy), international trade (e.g., grains, animal products, fertilizers), land use and management related to N cycling, such as manure recycling and wastewater treatment. Long-term datasets provide the best basis for a comprehensive assessment, e.g. starting from the year 1961 (the year when FAO database was available).

For N parameters, literature reviews are required to complement data on all of the relevant N cycling parameters, such as NH_3 emission ratios (% of total N applied), which are indicative of the local situation [34], such as dry climates in Australia. Some global models containing regionally specific parameters can also be used for the construction of such a dataset, e.g., IMAGE [35], IMAGE-GNM [36], GLOBIOM [37] and MAgPIE [38]. However, they may not contain all N related subsystems, for instance, as many models do not include an explicit industry subsystem. To understand the complete N cycling in a country, we propose a 14-subsystem model which enables a comprehensive assessment how N flows among different functional units, such as from cropland to livestock. This 14-subsystem model can also help to quantitatively assess and subsequently reduce the uncertainties of N fluxes calculation through robustly constraining the interacting fluxes among different subsystems [17]. The 14 subsystems include industry, cropland, grassland, forest, urban green land, livestock, aquaculture, pet, human, wastewater treatment, garbage treatment, surface water, groundwater, and atmosphere. Comprehensive N cycling within the 14-subsystem has been formally implemented in the CHANS model (Coupled Human And Natural Systems) for China [17], which can be easily adapted and applied to other countries. Other models can also be used to calculate a complete or parts of a N budget based on similar mass balance principles, such as IMAGE [35] and MAgPIE [38].

The basic principle of mass balance for the whole system and 14 subsystems is:

$$\sum_{h=1}^{m} \mathrm{IN_h} = \sum_{g=1}^{n} \mathrm{OUT_g} + \sum_{k=1}^{p} \mathrm{ACC_k}$$

where $\mathrm{IN_h}$ and $\mathrm{OUT_g}$ represent the N inputs and outputs, respectively, and $\mathrm{ACC_k}$ represents the N accumulations. Most N_r inputs transfer between subsystems, for example NO_x emissions from fossil fuel combustion deposit onto three major domains, natural land (i.e., forest, natural grassland and extensive graze land), managed grassland (including intensive grazing land and cropland) and freshwater and marine water bodies, and it can undergo further transformations and result in a variety of fluxes in and from these landscapes. N inputs to a country include HBNF, BNF, fossil fuel combustion, imports of N-containing products, and transboundary transports through atmospheric circulation and surface water flows. N outputs across national boundaries include riverine N transport to coastal waters, atmospheric circulation that advects N_r away from a country, denitrification, and N-containing product exports. More details of the N budget calculation for the 14 subsystems can be found in *SI Text*.

N fluxes validation and uncertainty

The validation of N fluxes calculated in the N budget model requires monitoring data from independent sources. The national scale N fluxes are downscaled to provincial, county or watershed scale to match and compare with the monitoring data. Two approaches can be used for downscaling: first, applying the national scale assessment to provincial, county or watershed scale if the available data is sufficiently spatially resolved; second, allocating total N fluxes on national scale to smaller scales through proxy indexes or modelling. The calibration of the modelled N budget is required if the validation results suggest a consistent and systematic bias. Then the newly calculated N fluxes need to be revalidated with monitoring data until sufficient agreement is achieved. Two types of monitoring data can be utilized for this: ground based monitoring and remote sensing (including Earth Observation) (Figure 4). Ground based monitoring covers N_r concentrations in the environment (air, water and soil). The data can typically be obtained from openly accessible repositories of regulatory monitoring networks, as well as published or ongoing research activities. However, the N_r concentrations monitored cannot be used to validate the N fluxes calculated within the budget model directly, as metrics and spatial resolution often differ. Thus, spatial patterns or temporal trends of these N_r concentrations in the environment are used to validate and calibrate the calculation of N fluxes. Meanwhile, some models which quantitatively assess atmospheric transmission of pollutants such as the Community Multi-scale Air Quality model (CMAQ) can be used to link the N fluxes to the N_r concentrations in the environment [39].

Remote sensing data can also be used to monitor the N_r concentrations in the air. Column concentrations of NH_3 and NO_2 from satellite instruments such as Infrared Atmospheric Sounding Interferometer (IASI), MOderate resolution Imaging Spectroradiometer (MODIS) or Multi-angle Imaging SpectroRadiometer (MISR) generate spatially explicit maps of N_r concentrations for comparison with N budget results [34, 40-42]. Some re-sampling and weighted mean methods are typically applied to make spatial correlations comparable [40, 41]. A spatial and temporal correlation analysis between N budgets and satellite monitoring results can be conducted for the validation (Figure 4). Normalized Difference Vegetation Index (NDVI) and land use data can be used to validate the national vegetation and crop production datasets to ensure spatial patterns of statistical data are robust [43].

The accuracy of N fluxes is critical for the subsequent costs-benefit analysis and design of management strategies. This accuracy is limited by our understanding of N cycles, the quality of the data, and the applicability of the calculated coefficients. The input-output calculations of the 14 subsystems are based on our current understanding of N cycles, and uncertainty quantifications have been introduced in areas where we consider our understanding to be less advanced, such as denitrification [17]. The quality of basic official data e.g. on food production and population consumption is important to the overall uncertainty of the estimation. We believe that the official statistics are a sufficiently reliable source of data for the analyses, and the confidence rating for the related N fluxes such as HBNF and N in food (and straw), goods production and consumption (from FAO statistics) can be considered as very high[32]. Nevertheless, N cycling parameters usually have large uncertainty ranges because they are affected by many natural (e.g. temperature) and anthropogenic (e.g. technology) factors [34]. Thus, N fluxes that are calculated from statistical data and N parameters have much higher levels of uncertainty compared to the primary N fluxes such as food production. To offset these uncertainties, the independently-calculated or measured data can be used to calibrate these N fluxes (Figure 4). For example, soil carbon sink can be used to validate the uncertainties of estimates on soil organic N accumulation [17].

Cost-benefit analysis

Benefits of N_r use are the results of increased production of the "good", decreased production of the "bad" outputs or decreased costs of measures or practices [8, 44]. N_r costs are the result of decreased production of the "good", increased production of the "bad" or increased cost of measures or practices. Cost-benefit analysis of N can be applied to estimate the societal cost associated with N mitigation strategies (including the cost of implementation of measures) or to calculate values and trends of societal net and gross cost of N pollution (excluding the cost of measures).

To quantify the societal value of these goods such as crops, livestock, biofuel, and non-fertilizer industrial N products, a straight forward approach would be to apply market prices and purchasing power parity (PPP) correction. Unlike the goods that can be valued by using marketing prices, other benefits such as ecosystem service (ES) need to be estimated based on non-market valuation approaches such as those presented in the framework of Millennium Ecosystem Assessment (MEA) [45]. Apart from the valuation of N_r contributions to climate change effects that can also be estimated based on carbon price on the global market, the non-market values of other services are mainly quantified using willingness-to-pay (WTP) approaches, or restoration costs [25] (Figure 4).

The costs include the market costs to produce synthetic ammonia and its derivatives, the costs of damage to the environment, human health, ecosystems, climate, and society (e.g., reductions of labour productivity and crop yield), and costs to mitigate N_r pollution. The costs of intended N_r uses are typically straightforward to quantify by including values based on market prices of resources and other inputs to produce these products or services [8]. For human health damage costs, the values for mortality and morbidity (e.g. loss of a healthy human life year), as well as costs arising from healthcare systems need to be quantified through N critical loading experiments and dose-response-effects modelling [8, 46]. For ecosystems and resource degradation, the restoration cost or WTP to prevent or restore biodiversity loss and associated ES can be used [25].

Scenario analysis and management

The findings from the first three stages provide an integrated picture of the N cycling in a country from the past to the present, and their costs and benefits. To maximize the benefits of N_r uses while minimizing its costs, scenario analyses can be conducted to understand how different measures affect the sustainable uses of N_r (Figure 4). Firstly, sensitivity analysis tests which parameters exert dominant effects on the target N fluxes by using N budget models such as MAgPIE and CHANS [17, 38]. Then, the potential changes in N fluxes and their costs and benefits under different scenarios can be assessed. Various management strategies can be identified based on the results of the scenario analysis, considering both the potential of N flux changes and the related costs and benefits.

Scenario analysis. For scenario development, several parameters, including NUE, N recycling ratio, dietary pattern and food waste ratio, have been identified to have substantial effects on the mitigation of N_r losses [17, 38]. Human N requirement (mainly food N) is determined by dietary patterns and food waste ratios, and the overall N requirement and loss (N budget) can be estimated through integrating the NUE and N recycling ratios[17]. These four parameters can be estimated based on following equations:

$$\mathrm{NUE} = \frac{\text{N in products}}{\text{Total N input for production}}$$

where NUE refers to the efficiency to produce N containing products in a system, such as cropland, livestock, aquaculture, etc. N in products refers to N contained in the final products such as crops, meat & eggs, fishes. Total N input for production refers to the N used such as N fertilizer in cropland and feed for livestock. High NUE refers to a higher ratio of N_r contained in final useful products, and lower amounts of N_r lost to the environment [5].

$$\text{N recycling ratio} = \frac{\text{N reused}}{\text{Total N residue}}$$

where N recycling ratio refers to the ratio of N_r reused for production, such as the manure recycled to cropland for production. N reused refers to the part of N_r residue or waste reused for production, and Total N residue refers to total N residue generated such as total manure generated. The N recycling ratio mainly includes the recycled content of livestock and human excretion and straw returned to the agricultural production systems. This can increase the NUE indirectly through reducing the overall N losses.

$$\text{Dietary pattern} = \frac{\text{Animal protein}}{\text{Total protein consumed}}$$

$$\text{Food waste ratio} = \frac{\text{Food waste}}{\text{Food supply}}$$

where dietary pattern refers to the ratio of human protein consumption provided by animal products such as meat and eggs. Total protein consumed includes both vegetal and animal proteins. The food waste ratio refers to how much of food supplied is not consumed, usually wasted during storage, distribution and disposal. Regulations of dietary pattern and food waste mainly benefit the sustainable N_r uses through reducing the overall N_r demands by the end-users[30].

To simulate these N_r uses and losses, shared social pathway (SSP) storylines present a useful approach to estimate the population, urbanization and per capita GDP in the future [38]. Many studies on the mitigation of N losses followed the scenarios of IPCC with regard to future projections of greenhouse gas emissions, although the behaviour of carbon is not always consistent with that of N [47]. Therefore, the new scenarios specifically designed with N in mind here are recommended for use in N assessments.

Management. Solutions for better managing N_r under different scenarios may not be adopted solely due to high cost, if benefits are not recognised or quantified [24]. Therefore the results from the cost-benefit analysis and scenarios analysis on the optimisation of N fluxes to achieve cost-effective solutions for a sustainable future need to be integrated. The costs and benefits of each scenario could be quantified to identify optimal solutions. Furthermore, whether these selected solutions for the sustainable use of N_r are feasible requires further analysis of the socioeconomic barriers [27, 48]. These barriers can be economic structure (e.g., farm size), population density, culture, religion, consumer or even dry climate. Thus, social scientists should be involved in assessing the feasibilities of the proposed solutions. Finally, several N sustainability indices can be used to translate the scientific results to the public and policy makers to make real impacts, such as the N footprint concepts[49]. N fluxes and their costs and benefits are incorporated into the indices to reflect the quality of products and their environmental effects.

Implications of N assessment

This paper presents a generally applicable framework for a comprehensive, 4-stage national scale N assessment, covering all relevant Nr issues towards a better N management in a country. While national N budgets have already been completed in some countries, N_r related challenges vary with regions and countries and are intricately linked with local socioeconomic development [7, 14, 17]. Parts of this framework have been successfully applied to EU[50] and China[17], compiling a comprehensive N budget and illustrating potential future trends under different scenarios. We believe that a wider application of the N assessment to other countries can contribute to a substantial improvement of global sustainable use of N.

The framework and methodology proposed in this study are inherently interdisciplinary and require the integration of expertise from both natural sciences (e.g., Environmental Science, Soil Science, Ecology, Earth Science, etc.) and social sciences (e.g., Economics, Management, Policy, Law, etc.). Unlike previous studies on N cycling, this study designs an approach for the development of a comprehensive, comparable N assessments, including the interaction between N cycling and socioeconomic issues. Novel interdisciplinary methods proposed here range from site-scale monitoring and validation, to regional surveys and remote sensing datasets, combined with budget calculation, modelling, econometric and policy assessment. This framework will advance our knowledge on how to sustainably use N_r at a national scale, and how to face the challenges of N_r releases under future global change and growing population pressures.

Application for China

To feed an increasingly affluent population, China uses about one third of global N_r to produce food. Nevertheless, it still imports over 100 million tons of grain to meet China's national food demand[32]. Unfortunately, a large amount of N_r is lost to the environment during the production and consumption of food at the country scale, resulting in serious environmental pollution in China. At the same time, substantial socioeconomic developments have taken place since the late 1970s [19, 51]. To solve the double challenge of producing more food with less pollution, we applied our framework of N assessment to China for the period of 1980 to 2015.

Nitrogen budget. Results showed that total N_r input to China increased from 25 to 71 Tg N yr^{-1} between 1980 and 2015, of which 74% and 89% derived from anthropogenic sources in 1980 and 2015, respectively (Figure 5). After input to the boundary of China, N_r cascades through the 14 subsystems, and produces about 20 Tg N yr^{-1} in food and feed, while losses to the environment amount to around 50 Tg N yr^{-1} in 2015. Agricultural sources are responsible for approximately 91% of total NH_3 emissions; fossil fuel combustion accounts for 90% of total NO_x emissions; agricultural and natural sources (forest and surface water) together dominate N_2O emissions in China. Agricultural sources and human sewage contribute most of the N_r discharge to surface water, while agricultural sources and landfill leaching are responsible for the bulk of N_r discharges to groundwater. More detailed information about the N fluxes in China can be found in Figure S1.

Nitrogen flux validation. The modelled N_r fluxes to the environment were validated using data from ground based national monitoring networks of air and water quality and remote sensing data providing column concentrations of NH_3 and NO_2 [19, 34]. N fluxes to air (NH_3 and NO_x emissions) were well validated using remote sensing data with a regression (R^2) of more than 0.7, while N fluxes to water showed a less strong regression (R^2 ~0.5). This is due to the complex N cycling processes which occur in water bodies and e.g. denitrification. Increasing the number of monitoring sites for water N concentrations could help to reduce the uncertainty by providing more data for a robust validation of N fluxes to water bodies.

Cost-benefit analysis. Integrating N_r emissions and population exposure assessments, we calculated that using 2015 N_r fluxes, N_r emissions to the air (including NH_3, NO_x and N_2O) caused the loss of 16.5 million life years annually in China, a much higher value than the loss of 2.6 million life years found in EU [8, 17]. If converted, these losses of life years equate to a monetary value of around 200 billion US dollars annually. Further analyses of other cost-benefit assessment components, such as ecosystem service impacts due to N_r loss to water bodies are still ongoing.

Scenario analysis. An explicit consideration of the following four proposed factors in the analysis could help to better explore potential interventions to mitigate N_r losses. We found that increasing N use efficiency, optimising diets, increasing N recycling and reducing food waste could decrease total N losses during food production and consumption by about 50%, 25%, 30% and 10%, respectively. Combining feasible changes in these four factors could reduce N losses by the year 2050 to about 60-70% of 2015 levels.

Management. However, to achieve these reductions, socioeconomic barriers need to be addressed as indicated previously. We found that increasing farm size (current average of <0.1 hectare each farm) is the crucial challenge for the implementation of regulatory measures in China, especially interventions to increase NUE and recycling ratio. High labour costs suggest a low level of mechanisation and automation in small farms, which inhibits the application of precision agriculture and fertilization technologies, as well as management based on scientific knowledge and information on application methods [27]. Increasing farm size has been integrated as a viable intervention into the recommendations to achieve the goal of a zero increase and even reduction in fertilizer use in China. Nevertheless, more sophisticated assessments are still ongoing to identify further socioeconomic barriers that inhibit the sustainable use of N_r in China.

SUPPORTING INFORMATION

SI text

Five tiers for the cost-benefit analysis

N budgets of 14 subsystems

SI methods

Nitrogen budget calculations for the 14 subsystems within the CHANS N cycle model

SI Figures

Figure S1. N cycling among the 14 subsystems in China in 1980.

Figure S2. Coupled Human And Natural Systems (CHANS) model structure.

SI Tables

Table S1-S10, parameters used within the CHANS model.

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Figure Legend

Figure 1. Major transformation pathways of the global N cycle. Red arrows represent the pathways of the human meditated N cycle; grey arrows represent the pathways dominated by microbial activities; green arrows represent the pathways dominated by plants; blue arrows represent the pathways dominated by atmospheric chemical reactions. Abbreviations: *BNF*, biological N fixation; CBNF, cultivated biological N fixation; *Denitri*, denitrification; *HBNF*, Haber-Bosch N fixation; *Nitri*, nitrification.

Figure 2. Simplified view of managing N for sustainable development highlighting the three major scientific questions. (Q1) How are N uses and losses affected by natural and human factors? (Q2) How to quantify the societal costs and benefits of N use? (Q3) What are the socioeconomic barriers constraining the more sustainable use of N? Nr, reactive N.

Figure 3. Conceptual diagram depicting the linkage between the DPSIR scheme and the framework of N assessment in this study. DPSIR, Driver–Pressure–State–Impact–Response; Q1-Q3 represent the three major scientific questions need to be addressed in Figure 2. (Q1) How are N uses and losses affected by natural and human factors? (Q2) How to quantify the societal costs and benefits of N use? (Q3) What are the socioeconomic barriers constraining the more sustainable use of N? NUE, N use efficiency.

Figure 4. An overview of the methodological framework. It describes the approaches to mass balance modelling, validation, cost-benefit analysis and management for the sustainable future use of N_r. BNF, biological N fixation; NDVI, normalized differential vegetation index; WTPs, willingness to pay.

Figure 5. A simplified N cycling schematic for China for the year 2015. Pathways marked in green refer to ‘natural’ fluxes (to some extent altered by atmospheric N_r deposition), those in blue are intentional anthropogenic fluxes, and those in orange are unintentional anthropogenic fluxes. Not all N fluxes were included due to space limits.

Nat, Natural; exp., export; wwt, wastewater treatment.

Figure 1

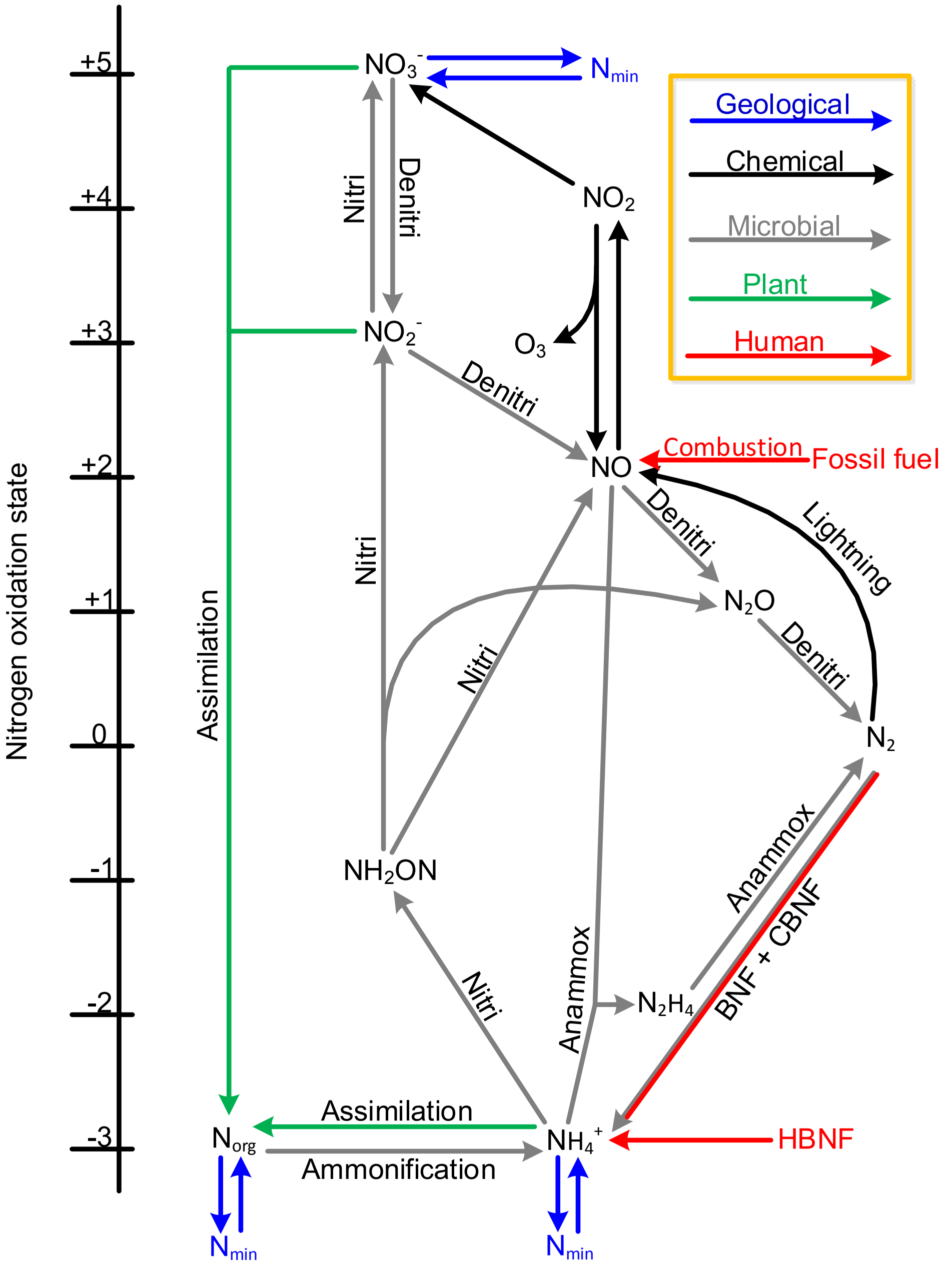

Nitrogen oxidation state
+5
+4
+3
+2
+1
0
-1
-2
-3
Geological
Chemical
Microbial
Plant
Human
NO3-
Nmin
NO2
O3
NO2-
NO
N2O
N2
NH2ON
N2H4
NH4+
Norg
Nitri
Denitri
Assimilation
Ammonification
Anammox
Lightning
Combustion
Fossil fuel
BNF + CBNF
HBNF

Figure 2

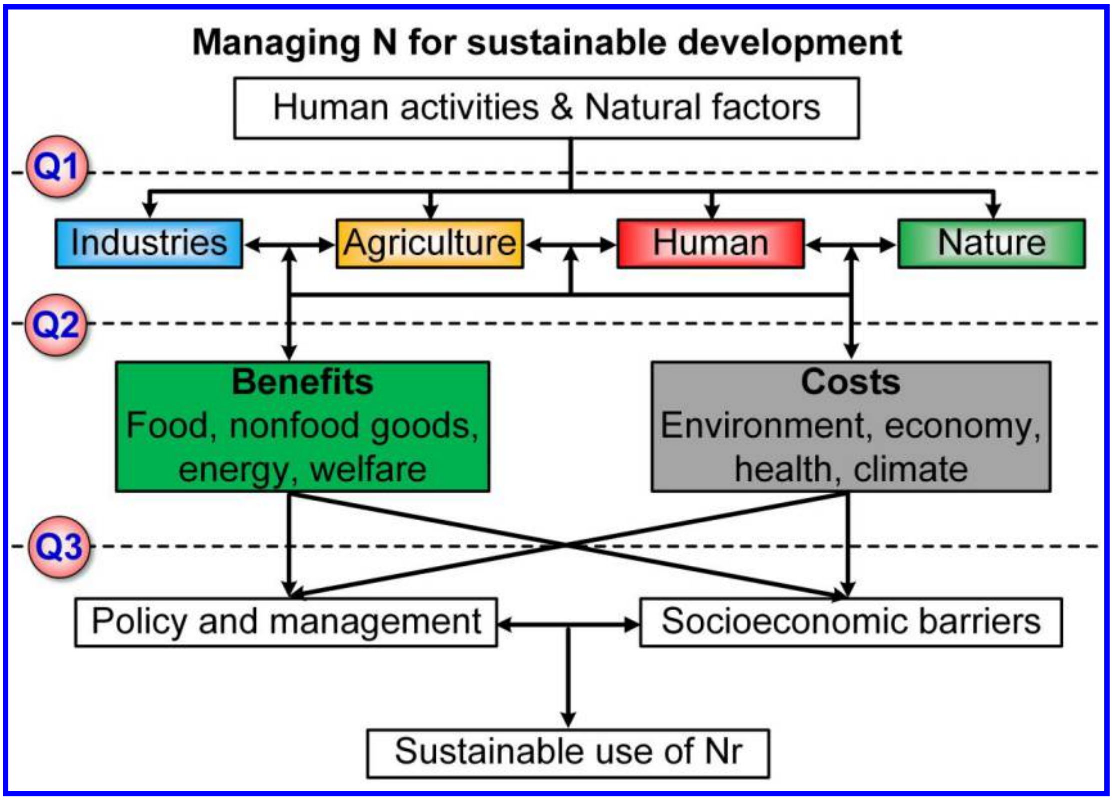

Managing N for sustainable development
Human activities & Natural factors
Q1
Industries
Agriculture
Human
Nature
Q2
Benefits
Food, nonfood goods, energy, welfare
Costs
Environment, economy, health, climate
Q3
Policy and management
Socioeconomic barriers
Sustainable use of Nr

Figure 3

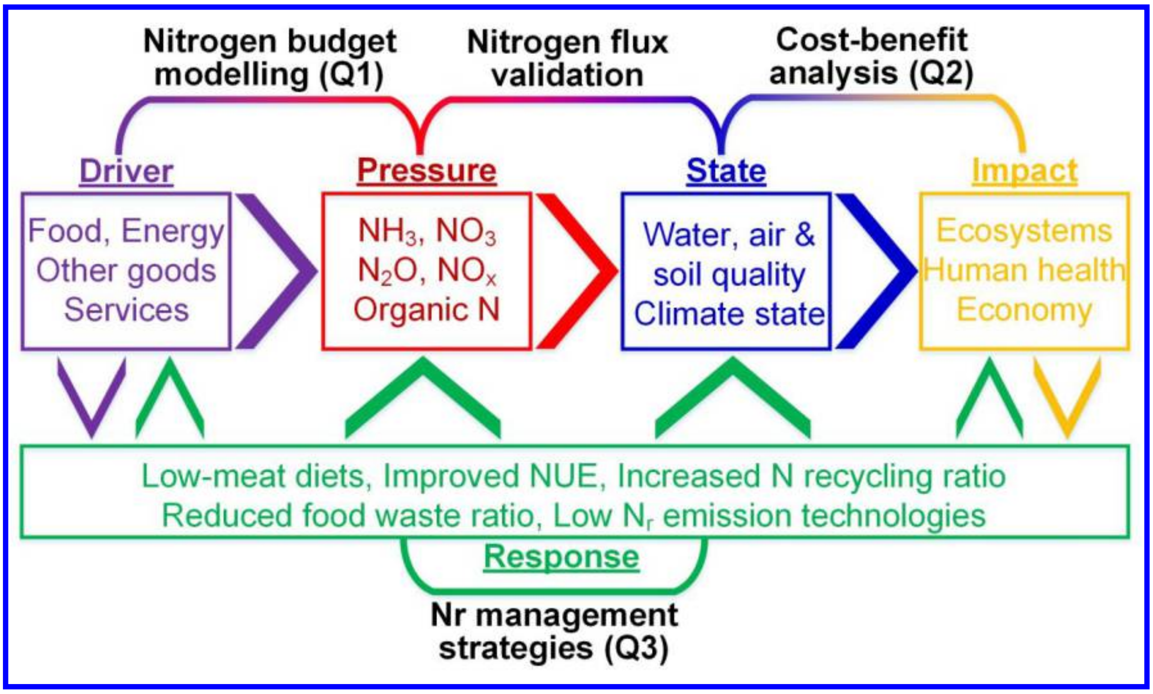

Nitrogen budget modelling (Q1)
Nitrogen flux validation
Cost-benefit analysis (Q2)
Driver
Pressure
State
Impact
Food, Energy
Other goods
Services
NH3, NO3
N2O, NOx
Organic N
Water, air &
soil quality
Climate state
Ecosystems
Human health
Economy
Low-meat diets, Improved NUE, Increased N recycling ratio
Reduced food waste ratio, Low Nr emission technologies
Response
Nr management strategies (Q3)

Figure 4

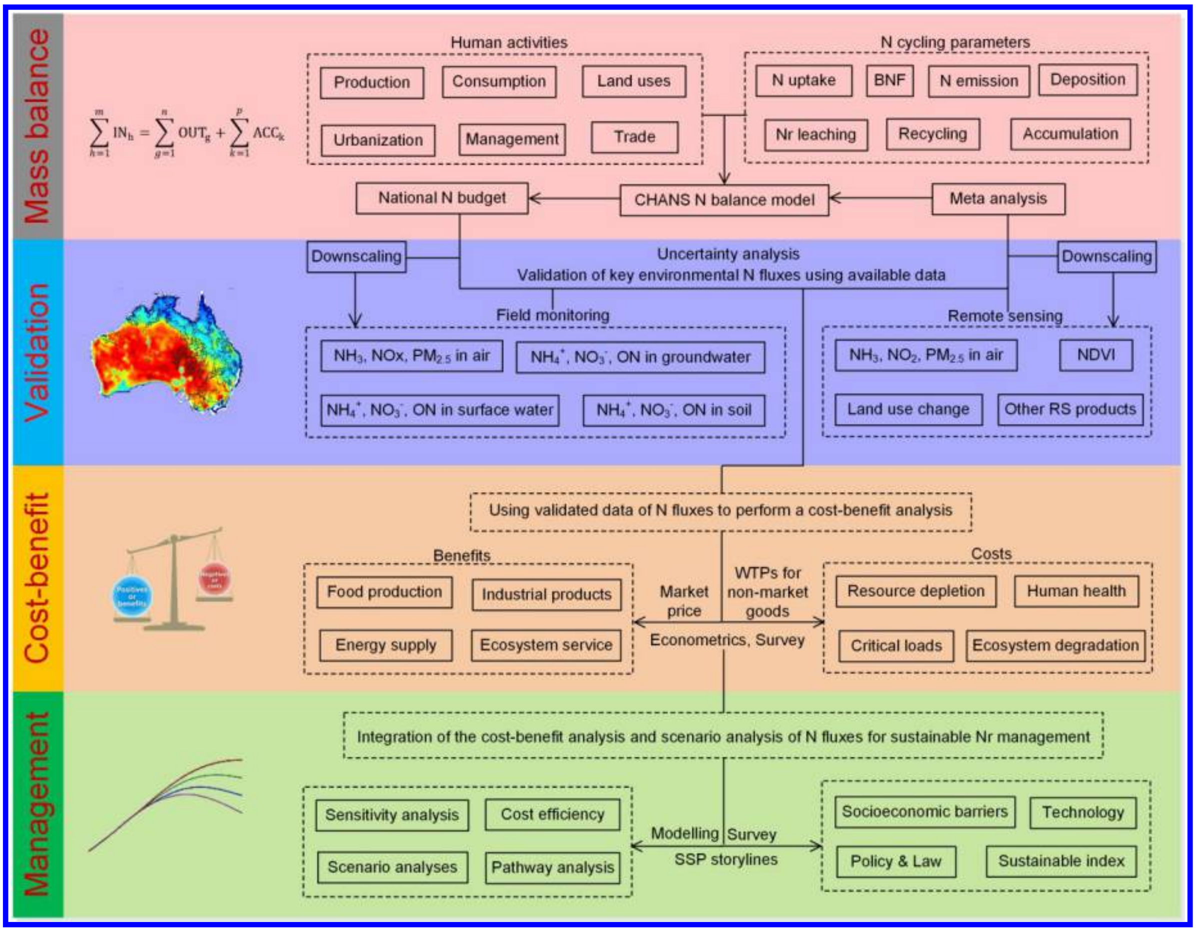
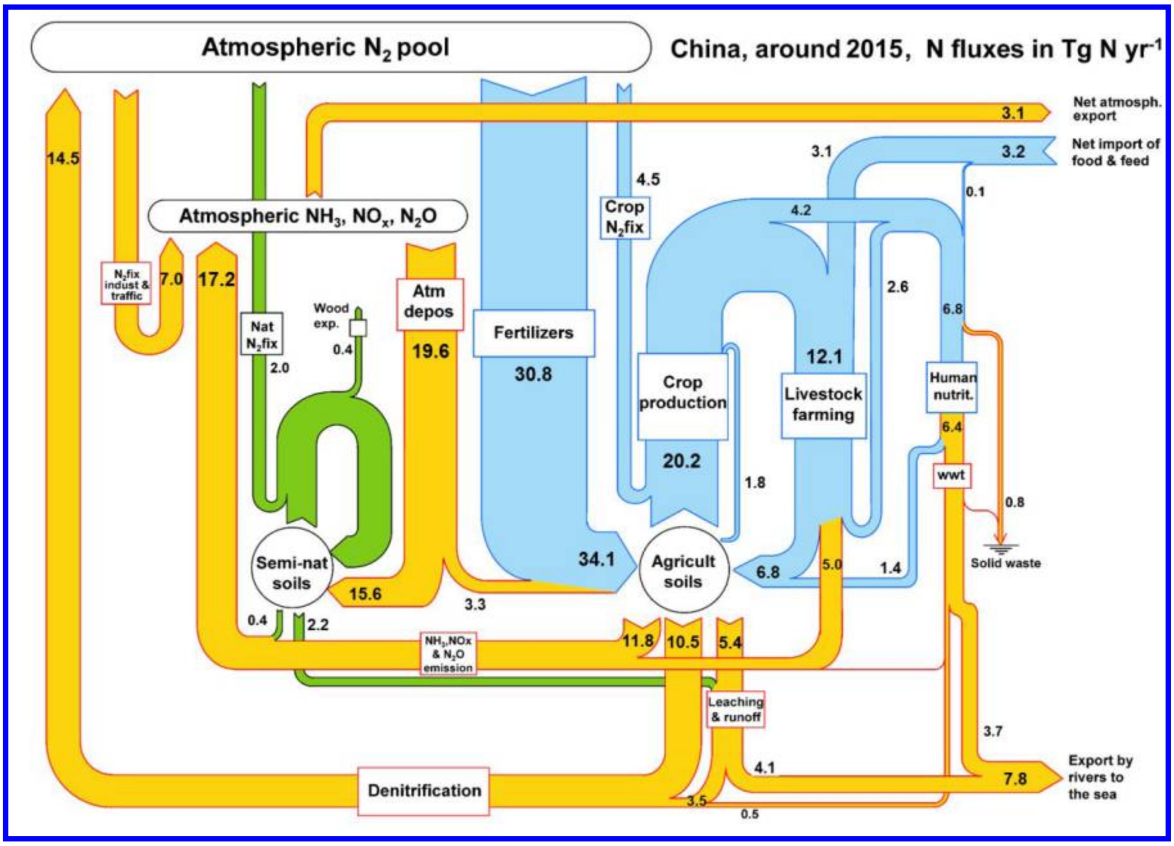
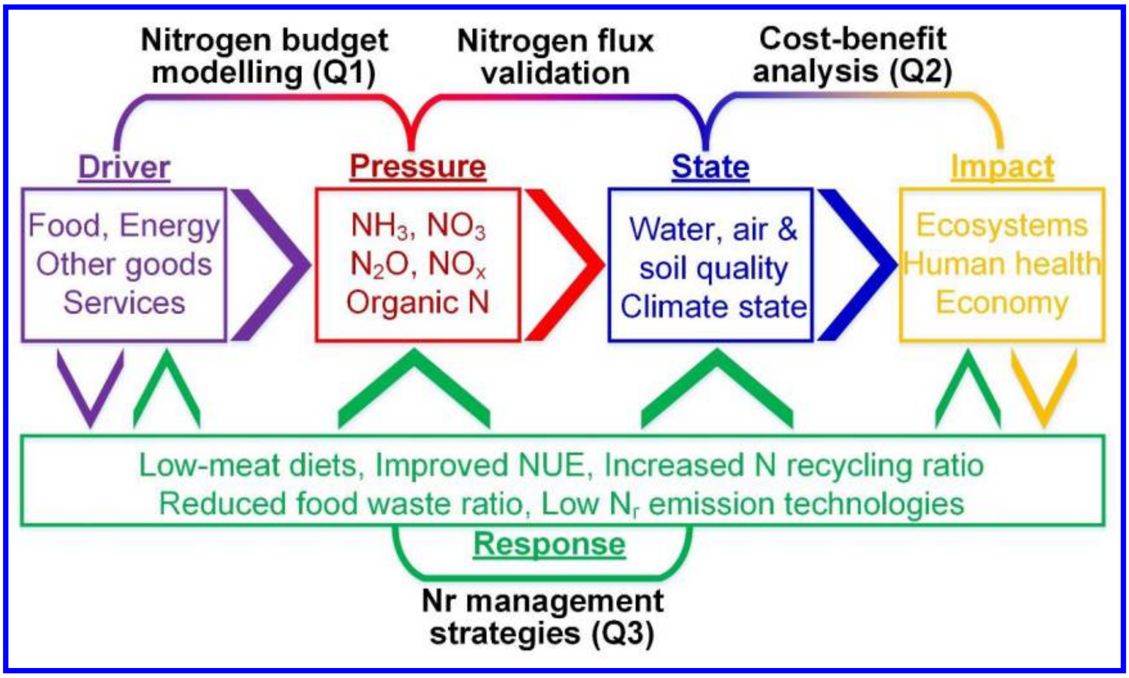

Mass balance
Validation
Cost-benefit
Management
$\sum_{h=1}^{m} IN_h = \sum_{g=1}^{n} OUT_g + \sum_{k=1}^{p} ACC_k$
Human activities
Production
Consumption
Land uses
Urbanization
Management
Trade
N cycling parameters
N uptake
BNF
N emission
Deposition
Nr leaching
Recycling
Accumulation
National N budget
CHANS N balance model
Meta analysis
Downscaling
Uncertainty analysis
Validation of key environmental N fluxes using available data
Downscaling
Field monitoring
Remote sensing
NH_3, NOx, $PM_{2.5}$ in air
NH_4^+, NO_3^-, ON in groundwater
NH_4^+, NO_3^-, ON in surface water
NH_4^+, NO_3^-, ON in soil
NH_3, NO_2, $PM_{2.5}$ in air
NDVI
Land use change
Other RS products
Using validated data of N fluxes to perform a cost-benefit analysis
Benefits
Food production
Industrial products
Energy supply
Ecosystem service
Market price
WTPs for non-market goods
Econometrics, Survey
Costs
Resource depletion
Human health
Critical loads
Ecosystem degradation
Integration of the cost-benefit analysis and scenario analysis of N fluxes for sustainable Nr management
Sensitivity analysis
Cost efficiency
Scenario analyses
Pathway analysis
Modelling
Survey
SSP storylines
Socioeconomic barriers
Technology
Policy & Law
Sustainable index

Figure 5


Atmospheric N₂ pool
China, around 2015, N fluxes in Tg N yr⁻¹
14.5
N₂fix indust & traffic
7.0
17.2
Atmospheric NH₃, NOₓ, N₂O
Nat N₂fix
2.0
Wood exp.
0.4
Atm depos
19.6
Fertilizers
30.8
Crop N₂fix
4.5
3.1
Net atmosph. export
3.1
3.2
Net import of food & feed
0.1
4.2
2.6
6.8
Crop production
20.2
1.8
12.1
Livestock farming
Human nutrit.
6.4
wwt
0.8
Solid waste
Semi-nat soils
15.6
3.3
34.1
Agricult soils
6.8
5.0
1.4
0.4
2.2
NH₃,NOx & N₂O emission
11.8
10.5
5.4
Leaching & runoff
3.7
4.1
Export by rivers to the sea
7.8
Denitrification
3.5
0.5


Nitrogen budget modelling (Q1)
Nitrogen flux validation
Cost-benefit analysis (Q2)
Driver
Food, Energy
Other goods
Services
Pressure
NH_3, NO_3
N_2O, NO_x
Organic N
State
Water, air &
soil quality
Climate state
Impact
Ecosystems
Human health
Economy
Low-meat diets, Improved NUE, Increased N recycling ratio
Reduced food waste ratio, Low N_r emission technologies
Response
Nr management strategies (Q3)