



A review of nitrogen flow in the anthroposphere to identify key control sectors

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Received: 25 March 2023 / Accepted: 26 October 2023 / Published online: 17 November 2023
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Abstract

Mitigating the negative environmental impacts caused by nitrogen (N) requires an understanding of its flows across and through various systems. This study fills a research gap by identifying the key N sink and sources with flows at three geographical scales (city, region, and country) using a comprehensive literature review. For a systematic literature review, the PRISMA 2020 method was used to select thirty-three studies spanning from 1995 to 2023. The findings of the study indicate that at the city scale, N enters primarily as food and miscellaneous (e.g., fossil fuel) flow and exits as emission and soil losses, while the primary stock of N occurs in landfills. At the region scale, the inflow of N is via feed and fertilizers and the main outflow is emissions and food; the N stock occurs in the soil available in the ecosystem. At the country scale, N imports come from Feed and Fertilizer, while the N outflows occur through emission and food with majority of N stocks held in the soil. The major outflows and stocks identified in this assessment can have potential to improve N management in future studies by acting as a guide for selection of key sectors, appropriate geographical scales, and flows. The main limitation in analysis originates from the varying scope of studies available in the literature. It would be better to have the data available for multi-year time periods at city and region scale so as to achieve more confidence in findings of future N flow studies.

Keywords Nitrogen metabolism · Material flow analysis (MFA) · Geographical scale · Waste management · Resource management · Circular economy

Introduction

Nitrogen (N) and phosphorus are essential elements for sustaining life. For N, the atmosphere is indeed an unlimited source; however, energy is required for the industrial conversion of N₂ (nitrogen) to chemical compounds that plants can use, e.g. ammonium and nitrate. As a result, the amount of N available in the anthroposphere is primarily limited by energy supply (Winiwarter et al. 2020). The reactive N (reduced inorganic forms of N, oxidized inorganic forms, and organic compounds) may be absorbed by bacteria and plants (Galloway et al. 2004). However, excess reactive N can cause the greenhouse effect and damage the ecosystems, leading to acidic rain, lake and offshore eutrophication,

and loss of local, national, and global biodiversity (Zhang et al. 2016). Effective resource management is important for ensuring food production and reducing environmental strain. This can be done by reducing nutrient losses, increasing nutrient usage efficiency and recycling throughout the system to address the global N issue and ensure a sustainable food supply, across different levels within the anthroposphere (Kaltenegger et al. 2021; Tonini et al. 2014).

Developing more effective policies and management strategies necessitates a deeper comprehension of how N flows across various processes in different geographical scales. The term ‘geographical scale’ means the extent of the area being considered in the study, i.e. city, region and country. The term ‘Sector’ refers to a certain type of system with a set of processes having specified characteristics that work together as elements of a larger process. For example, crop production, waste management, and streams and rivers all are different sectors. The amount of N that reaches a specified geographical scale in a given time period through a given channel is referred to as N inflow. The amount of N that departs a specific geographical system in a given period

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through a given channel is referred to as N outflow (Allesch and Brunner 2015). N stock is the amount of N retained in a sector within a specified geographical scale at any given time. Internal flow refers to the amount of N that moves from one sector to another across a channel within a specific geographical scale in a particular time. N recycling flow refers to the amount of N recovered from waste and recirculated to any sector within a geographical scale at any particular time (Chowdhury et al. 2014).

The outcome of any N flow analysis depends on how the system under consideration is defined in terms of geographical scale and key sectors of N flow. The significance and size of the key sectors for N flow vary from one geographical scale to another, and the priority areas of N flow might be different at various geographical scales. Therefore, the focus and system boundaries of the studies could impact the results of the N flow analysis. For example, if a study only considers the N flow within the agricultural system, it may not capture the full picture of N flow in a region or country. Similarly, if a study only considers the N flow at the city scale, it may not capture the N flow at the regional or country scale.

Several studies have quantified N flow at different geographical scales (Amann et al. 2021; Andersen et al. 2010; Antikainen et al. 2005; Buathong et al. 2013; Cai et al. 2022; Firmansyah et al. 2017; Guo et al. 2021; Lederer et al. 2015; Sokka et al. 2004; Zhang et al. 2016). Three geographical scales, namely city, region and country, are being considered in this study. The city scale is defined as a scale of the study which considers the urban ecosystem or any specific treatment system for the whole city. The country scale refers to the level of analysis that focuses on the N flows within a country. The regional scales are the systems having an extent between that of a city and a country. The criterion of categorizing data into different geographical scales based on area (hectare or km²) was not considered in our study owing to lack of required data in the literature.

An initial set of studies centred around N flow was chosen to conduct this assessment. These studies were selected based on the criteria of utilizing substance or material flow analysis (SFA/MFA) as a quantitative methodology to evaluate the movement of N within a given system. MFA is a systematic methodology used to track and quantify the movement of materials or substances within a specific system, such as an industrial process, a city, or an ecosystem (Burgara-Montero et al. 2012). The MFA analysis can be an effective tool in creating a management strategy that is appropriate for a country's economy and the surrounding environment (Kupkanchanakul and Kwonpongsagoon 2011). Similarly, substance flow analysis (SFA) is a methodology used to quantify the flow of substances, or compounds through a system or a specific region, such as a country or a city. SFA is also known as substance flow assessment, MFA

of substances, or substance flow modelling (Brunner and Rechberger 2003).

These studies can make it easier for researchers to determine the nitrogen flow quantities depending on the scale of the system, minimizing N loss, and offering choices for N recovery. By conducting a systematic and in-depth evaluation of thirty-three studies of N flow based on MFA, this study examines the nature and extent of the important N flow at different geographical scales. This evaluation will be based on a review of key sink and sources with flows. This assessment is expected (i) to identify the key N management sectors at different geographical scales; (ii) to identify important flows for N at various geographic scales; (iii) to bring out the shortcomings in the available literature on N flow analysis and discuss future research options for developing baseline condition for better N management decisions. The study does not focus on a particular location or area of interest, but rather provides a general overview of the nature and magnitude of N sink and sources of flows at different geographical scales. The limitation of this assessment is that it only provides details about N flows in any specific scale and does not provide any detailed information on how to recycle and recover N.

Method

This review considers only those MFA studies that examine the changes in N flow. A systematic literature review is a rigorous and structured approach to identifying, analysing, and synthesizing relevant research studies on a specific topic or question. This study also uses a systematic literature review to provide a comprehensive understanding of N flow through various geographical scales. To conduct a systematic literature review, we preferred the updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 method over others because it provides a comprehensive, evidence-based, standardized, and widely recognized approach (Page et al. 2021). A process was implemented to describe the selected information sources, search method, criteria for selection, methods for data extraction, and analysis. In this study, a systematic search of articles was conducted using three electronic databases: Scopus, Web of Science (WoS), and Wiley Online Library (WOL). Specific inclusion and exclusion criteria were established in order to only choose and include papers that were determined to be relevant for this study (Table 1).

Following PRISMA 2020 guidelines, the systematic literature review was done in five phases (Page et al. 2021). The first phase consisted of an initial search of the electronic databases Scopus (267), WoS (110), and WOL (59) for the relevant material. According to the inclusion (IC1, IC2, IC3) and exclusion (EX1, EX2, EX3) criteria, 56 papers were

Table 1 Criteria used for selection of studies

Inclusion criteria	Exclusion criteria
IC1: Journal articles, book and book chapter	EX1: Conference papers, proceedings of congresses, and other non-peer-reviewed publications
IC2: The article is written in English	EX2: The article is not written in English
IC3: The article is peer-reviewed	EX3: The article is not peer-reviewed
IC4: The study considered N and MFA	EX4: The study considered N but not MFA or MFA but not N
IC5: The study considered details about external interactions in terms of waste (Solid, Liquid) being generated from human settlements	EX5: The study considered an experimental/pilot setup; OR a treatment plant without any detailed information about input to the plant

found ineligible based on paper type, language, and peer-review criteria. The duplicate studies (total in 88) among three databases were also excluded in this phase; the inclusion (IC4) and exclusion (EX4) criteria were applied in the second phase by reviewing the titles and abstracts of 292 papers and 85 publications were screened out. In the third phase, 19 papers were excluded from further analysis because they were not available in full text. In the fourth phase, a total of 188 papers were carefully screened for eligibility and 152 studies were excluded as a result of EX4 and EX5. Finally, based on IC5, the full text of the remaining 33 papers were reviewed thoroughly for relevance to our criteria and research questions. The described process is summarized in a PRISMA flow diagram (Fig. 1). The majority of these studies used SFA/MFA, employing the concept of mass balance within a system (Allesch and Brunner 2015).

Result and discussion

Key sectors of N flow at various geographical scales

While analysing the flows of any substance in anthropogenic systems, the criteria for defining sectors may vary depending on the specific scale of the study and the type of system being analysed. However, some common criteria include the sector's contribution to the material flow being analysed, its level of resource consumption or waste generation, and its potential for pollution or environmental harm. For example, at the city scale, N enters primarily as food and miscellaneous (fossil fuel mainly) imports and exits as emission and soil losses, while the primary stock of N occurs in landfill so household, atmosphere and waste management sector become important. To compare the importance of sectors at various levels, it is important to consider the key sectors of N flow studies at different scales. The MFA method allows for the comparison of different areas of study by identifying the nature and magnitude of N inflows, outflows, stocks, internal flows, and recycling flows at different geographical scales. Table 2 defines the importance of sectors and flows

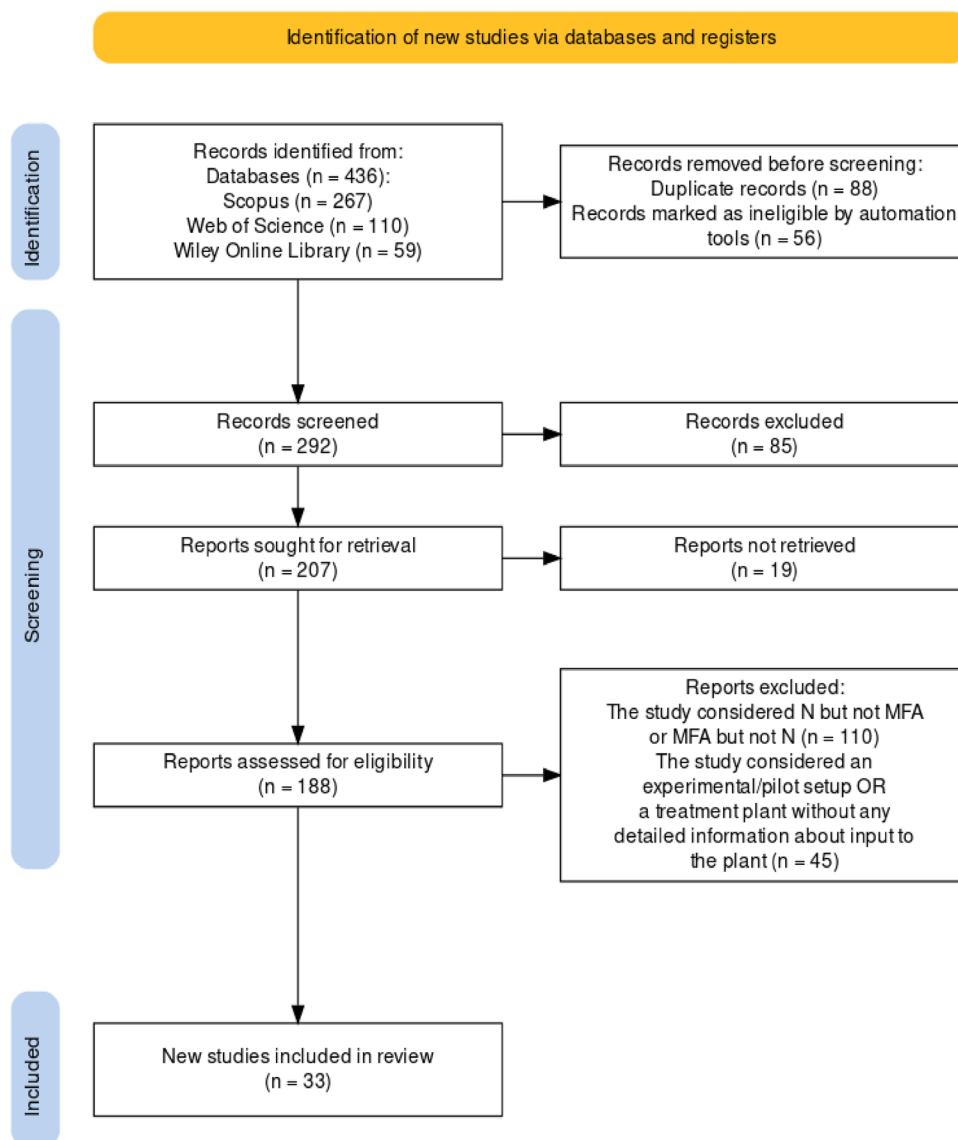
by looking at their frequency of occurrence in studies at different geographical scales.

Important sector refers to a sector which is frequently affecting N flow at a geographical scale, e.g. water-related (surface water, groundwater, ocean, river, and canal), soil-related (agricultural soil, forest soil and crop production), consumption-related (household, market, industry, livestock, animal husbandry) and waste-related (solid waste, wastewater, landfill, composting, incineration, onsite sanitation systems). The selected studies are analysed to understand the occurrence frequency of these sectors at various geographical scales. Among the sectors, consumption-related sector has been found to occur in 89–100% of studies depending on the geographical scale. Other important sectors are atmosphere, waste-related, soil-related and water-related, which also occur in more than 50% of the studies. The important flows include exchange with water- or soil-related sector and exchange with the atmosphere [emission; biological nitrogen fixation (BNF); deposition on soil]. The sectors associated with various studies are depicted in detail in Online Resource Table A-1. Based on the information provided (Online Resource Table A-1), the selection of suitable sectors depends on the focus of the study or the type of system being analysed in the geographical scale. N flow priority areas may vary across different geographical scales.

Key inflows and outflows at various geographical scales

Understanding the important N inflows and outflows associated with a specific geographical scale is crucial in deciding the priority areas of N management. Online Resource Table A-2 presents the findings of the selected N flow analyses in terms of inflows and outflows. To demonstrate the important N inflows and outflows at city scale, a case study from St. Eustatius, Netherlands, has been described. St. Eustatius is a small tropical island in the Caribbean and is officially a special municipality of the Netherlands. The study investigated N flow across the combined (urban and agricultural) ecosystem of St. Eustatius in the year 2013 (Firmansyah et al. 2017). The study estimated the total N input

Fig. 1 PRISMA 2020 flow diagram for this study



of 65,304 kg/a (kilogram per annum), with a total outflow of 59,890 kg/a. The remaining N of 5414 kg was held as stock (key stocks to be discussed in “[Key stocks at various geographical scales](#)” section) in various areas of the city. Human food (19,591 kg/a N, or 30% of total inflow) and BNF (41,141 kg/a N, or 63% of total inflow) were the two most important inflows to the public household and crop production from outside of St. Eustatius (Online Resource Table A-4). The residential sector consumed the majority of this imported nitrogen, resulting in significant release of N to the wastewater. As wastewater treatment is not being practiced, the majority of N ends up in soil finally.

Key inflows at various geographical scales

Figure 2 shows a comparison of the quantity of key N inflows at various geographical scale. The primary N inflow

has been noted in most of city-scale studies given in Fig. 2a as either food, miscellaneous (e.g. fossil fuel) or BNF. N import as food was identified to account for about 68%, 34% and 30% of the total N flow through the city studied in Aramaki and Thuy (2010), Danius and Burström (2001) and Firmansyah et al. (2017), respectively. Apart from food, significant N inflows can also occur at the city level through the import of BNF, which accounted for 63% of total inflow in the St. Eustatius, Netherlands, in 2013 (Firmansyah et al. 2017). The majority of studies indicate that food plays a significant role in the total inflows at city scale. While developing a city-scale N management strategy, all aspects of food consumption and waste should be evaluated. Although it may lead to marginal improvement in terms of quantity, the environmental impact may be significant (Li et al. 2020).

At the region scale, the predominant N inflows have been identified as feed, fertilizer, BNF and food (Fig. 2b). The

Table 2 Frequency table for various sectors and flows at different geographical scales

Sectors/flows	Geographical scale	Number of occurrences	% of occurrence
<i>Important sectors</i>			
Water-related (Surface Water, Ground Water, ocean, river, canal)	City	5	83
	Region	18	100
	Country	6	67
Soil-related (agricultural soil, forest soil, crop production)	City	5	83
	Region	17	94
	Country	7	78
Consumption-related (Household, market, industry, livestock ^a , animal husbandry ^b)	City	6	100
	Region	18	100
	Country	8	89
Atmosphere	City	5	83
	Region	18	100
	Country	8	89
Waste-related (solid waste, waste water, landfill, composting, incineration, onsite sanitation systems)	City	6	100
	Region	16	89
	Country	7	78
<i>Important flows</i>			
Exchange with atmosphere (emission; BNF; Deposition on soil)	City	6	100
	Region	17	94
	Country	7	78
Agriculture (Chemical fertilizer, manure)	City	5	83
	Region	15	83
	Country	7	78
Miscellaneous (raw material, non-food goods, fossil fuels, chemicals, vehicles, rice hull powder, earth worms)	City	6	100
	Region	14	78
	Country	6	67
Exchange with water or soil related sector (water, wastewater, leaching, runoff, erosion)	City	6	100
	Region	16	89
	Country	8	89

^aLivestock refers to the cattle raised for food production; ^bAnimal husbandry refers to care, breeding, and management of all types of animals, including livestock

study by (Coppens et al. 2016) found that N inflow as BNF import accounted for around 69% in Flanders, Belgium. N feed was identified to account for about 99% of the total N flow through the anthropogenic system of Bang Pakong basin, Thailand (Kupkanchanakul and Kwonpongsagoon 2011). N import as fertilizer was found to account for about 41% of the total annual N inflow by Boh and Clark (2020) in Ontario, Canada, while another study in Central Arizona–Phoenix, USA (Baker et al. 2001), estimated N fertilizer accounts for about 25% of the total inflow. Food was found to account for nearly 15% of the total N inflow in three region scale studies performed in Central Arizona–Phoenix, USA (Baker et al. 2001), Flanders, Belgium (Coppens et al. 2016), and Red river delta, Vietnam (Tran and Weichgrebe 2020). It can be concluded that in the absence of N fertilizer production industry, the major N inflow at the regional scale

occurs either through the import of chemical N fertilizer or animal feed, and with its presence, the main N inflow usually occurs as BNF.

The predominant N inflows at the country scale have been identified as feed, fertilizer, BNF and deposition (Fig. 2c). The study by (Luo et al. 2018) found that N inflow as BNF import accounted for around 60% in China. N deposition was identified to account for about 34% of the total N flow through the crop-livestock system of Austria (Thaler et al. 2015). A study from Finland investigated the food production and consumption sectors for the analysis of N flow in 1995–1999; it was discovered that chemical N fertilizer imports accounted for about 65% of the total inflow (Antikainen et al. 2005). Similarly, another study from Austria discovered that chemical N fertilizer imports accounted for about 32% of the total inflow (Thaler et al. 2015). Manure

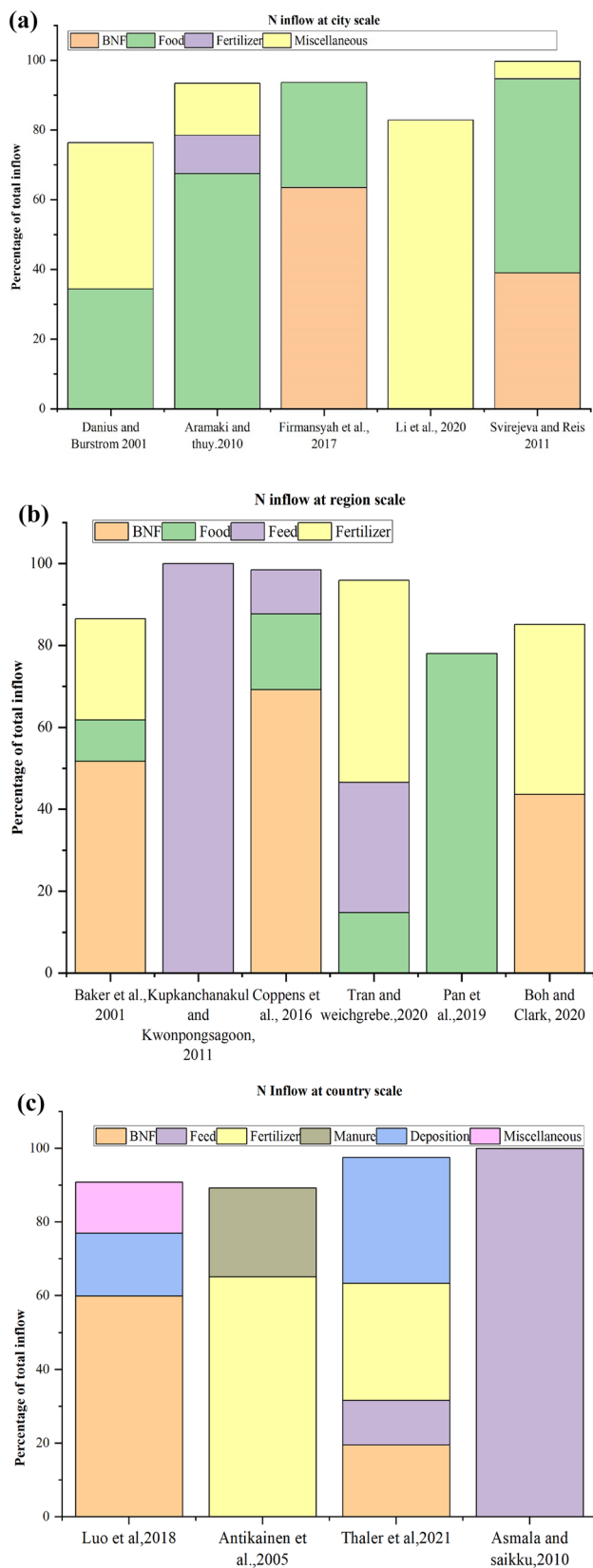


Fig. 2 Key N inflows at the **a** city, **b** region, and **c** country scale. Flows less than 10% of total inflows are excluded

import was identified to account for about 24% of the total N flow through the food production and consumption sectors of Finland (Antikainen et al. 2005). Feed was found to account for nearly 12% of the total N inflow in a study performed in Austria (Thaler et al. 2015). Together BNF and deposition accounted for approximately 53% of the total inflow for crop-livestock system (Thaler et al. 2015) and 77% of the total inflow for urban ecosystem (Luo et al. 2018). According to the findings of these studies, in the absence of a fertilizer manufacturing industry, the main N inflow at the country scale originates from the import of chemical N fertilizer or BNF.

According to findings of this study, the primary source of N (in decreasing order) is food, miscellaneous (e.g. fossil fuel) and BNF at the city scale; feed, fertilizer, BNF and food at the region scale; feed, fertilizer, BNF and deposition at the country scale. As a result, future N management decisions should prioritize lowering N input through these materials (Aramaki and Thuy 2010) and by substituting waste-derived N for chemical fertilizer in agricultural sector (Antikainen et al. 2005).

Key outflows at various geographical scales

The intensity of the important N outflows at different geographical scales is depicted in Fig. 3. The magnitude of the major N outflows at city level is depicted in Fig. 3a. The main outflows of N have been recorded as emissions to atmosphere, soil loss, exported food and wastewater. Exported food and emission to atmosphere were found to be approximately 71% of total outflow in Västerås municipality, Sweden (Danius and Burström, 2001). Soil losses (runoff, leaching) were found in two city-scale studies as significant N outflow. Soil losses were determined to be approximately 45% and 68% of total outflow in Haiphong, Vietnam (Aramaki and Thuy 2010), and St. Eustatius, Netherlands (Firmansyah et al. 2017), respectively. Emission was found to be approximately 15% of total outflow in Västerås municipality, Sweden, for urban ecosystem (Danius and Burström, 2001), and 30% of total outflow in St. Eustatius, Netherlands, for urban-agricultural system (Firmansyah et al. 2017). Other significant city-scale N outflows have been identified as wastewater. N outflow from soil to aquatic environment is inefficient because it contains soluble nutrients that are lost to agricultural commodity producers or even other end consumers, and it could contribute to algal blooms of waterbodies. The fertilizer use, agriculture, particularly farm animal manure, are a part of growing industry and the most significant source of N emissions to the atmosphere. As N flows have increased, both direct and indirect adverse effects on human health and the environment have increased (Galloway et al. 2004; Kaltenecker et al. 2021; Kaltenecker and Winiwarter 2020; Winiwarter et al. 2020).

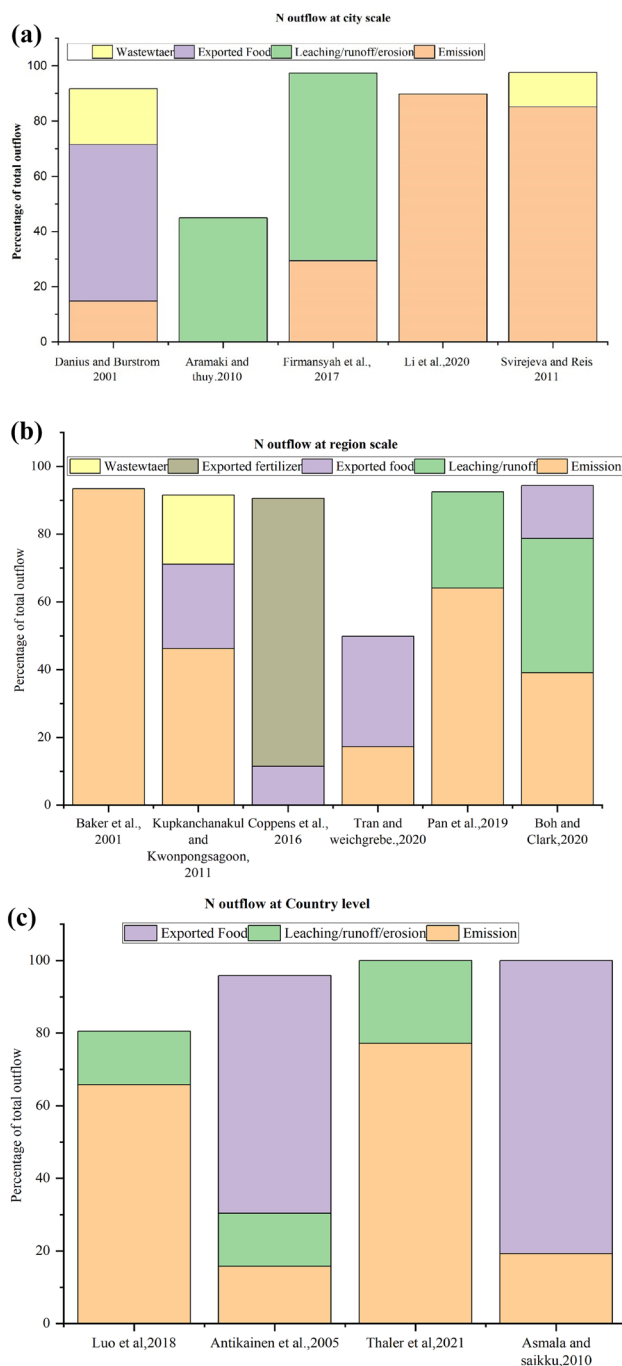


Fig. 3 Key N outflows at the **a** city, **b** region, and **c** country scale (flows less than 10% of total outflows are excluded)

On a region scale, the main outflows of N have been recorded as emissions to atmosphere, exported food and soil loss (Fig. 3b). N emissions are considered key outflows at the regional level as these contribute more, primarily due to the larger land area available for the transmission of N gases on a region scale. The emissions were found to be approximately 93% of total outflow in Central Arizona–Phoenix, USA, for urban ecosystem (Baker et al. 2001), 46% of total

outflow in Bang Pakong basin, Thailand, for animal production system (Kupkanchanakul and Kwonpongsagoon 2011), and 64% of total outflow in Beijing, China, for urban ecosystem (Pan et al. 2019). Similarly, food export was found to be the dominant N outflow, accounting for 25% of the total N outflow in Bang Pakong basin, Thailand (Kupkanchanakul and Kwonpongsagoon 2011), and 33% in Red river delta, Vietnam, for agricultural and food system (Tran and Weichgrebe 2020). The vast majority of these outflows are inefficient and environmentally hazardous.

The source and intensity of significant N outflows have been observed to vary across countries at the country scale studies. In four of the nine country scale studies evaluated, emissions to atmosphere, exported food, soil loss were found as the principal outflows (Fig. 3c). Emission was found to be approximately 16% of total outflow in Finland for urban ecosystem (Antikainen et al. 2005), 20% of total outflow in Finland for food production and consumption system (Asmala and Saikku 2010). Soil losses were determined to be approximately 15%, 15% and 23% of total outflow in Finland (Antikainen et al. 2005), China (Luo et al. 2018), and Austria (Thaler et al. 2015), respectively. Exported food was found to be approximately 66% and 81% of total outflow in Finland (Antikainen et al. 2005) and (Asmala and Saikku 2010) for 1995–1999, respectively.

Table 3 and Fig. 3 provide an overview of the significant N outflows at different geographical scales. Each of these indicates that a considerable amount of N is lost as unproductive outflows from the system, such as soil losses and emissions in city and region scale. The unproductive outflows may eventually reach surface water bodies, soil and atmosphere. Several studies have reported (Amann et al. 2021; Aramaki and Thuy 2010; Baker et al. 2001; Danius and Burström, 2001; Galloway et al. 2004; Jin et al. 2021; Kobayashi and Kubota 2004; Mayor et al. 2023; Pharino et al. 2016; Sinha et al. 2022; Xing et al. 2023) nutrients (i.e. N and phosphorous) discharge to water bodies as the major cause of eutrophication. Reducing nutrient flow to lakes and rivers can considerably mitigate these issues. As a result, future N management practices should include adequate steps to promote N recycling and recovery at various geographical scales in order to limit discharge to water bodies. Rana et al. (2022) perform a scenario analysis for examining the full spectrum of environment-friendly possibilities for the reuse and recovery of N.

Key stocks, internal flows and recycling flows at various geographical scales

The findings on key N stocks, internal flows, and recycling flows at different geographical scales are summarized in Table 4 and online resource Table A-2 and online resource Table A-3. For example, to illustrate the

Table 3 Intensity of key N inflows, outflows and stocks through various systems at different geographical scales

S.No.	Geographical scale	Location, country	Type of system	Year(s) of flow	Measuring units (as N)	Inflow value	Outflow value	Stock value (as given)	References
1	City	Västerås municipality, Sweden	urban ecosystem	1998	t/year	11,358	7410	NA	(Danius and Burström 2001)
2		Paris Metropolitan Area, France	urban ecosystem	2006	Gg/year	113	96	17	(Svirejeva-Hopkins and Reis 2011)
3		Haiphong, Vietnam	Urban Ecosystem	2008	g/person/day	40	29	3	(Aramaki and Thuy 2010)
4		Bangkok city, Thailand	sanitation system	2012	t/year	51,897	28,379	NA	(Buathong et al. 2013)
5		St. Eustatius, Netherlands	urban-agricultural system	2013	kg/year	65,304	59,890	5414	(Firmansyah et al. 2017)
6		Xiamen, China	Urban-Coastal Ecosystem	2015	t/year	404	NA	202	(Li et al. 2020)
7	Region	Central Arizona–Phoenix, USA	Urban Ecosystem	1995	Gg/year	91	78	13	(Baker et al. 2001)
8		Kasumigaura Bay, Japan	Agricultural and food system	1997	kg/year	NA	NA	13	(Kobayashi and Kubota 2004)
9		Catalonia, Spain	Urban Ecosystem	1997	N/A	NA	NA	NA	(Bartrolí et al. 2001)
10		Huizhou, China	Urban Ecosystem	1998	t/year	95,600	56,200	NA	(Ma et al. 2008)
11		Illinois, USA	Agricultural system	2002	Mt/year	1	2	–0	(Singh et al. 2017)
12		Bang pakong basin, Thailand	Animal production	2005	t/year	15,005	11,250	3755	(Kupkanchanakul and Kwongpongsgoon 2011)
13		Hanam province, Vietnam	Agricultural and sanitation system	2008	t/year	494	414	80	(Do-Thu et al. 2011)
14		Flanders, Belgium	Urban Ecosystem	2009	kg/cap/year	130	201	–71	(Coppens et al. 2016)
15		Day-Nhue river basin, Vietnam	Agricultural system	2010	t/year	1,11,206	NA	36,065	(Do and Nishida 2014)
16		Ratchaburi and Samut Songkhram province, Thailand	urban ecosystem	2010	t/year	69,802	68,516	1277	(Pharino et al. 2016)
17		Busia district, Uganda	Agricultural system	2010	t/year	2000	2200	–130	(Lederer et al. 2015)
18		Ontario, Canada	Food production and consumption system	2011	kt/year	511	353	158	(Boh and Clark 2020)
19		Sio-Malaba-Malakisi River Basin, Kenya and Uganda	Agricultural, food and WM system	2014	kg/ha/year	NA	NA	386	(Amann et al. 2021)

Table 3 (continued)

S.No.	Geographical scale	Location, country	Type of system	Year(s) of flow	Measuring units (as N)	Inflow value	Outflow value	Stock value (as given)	References
20		Red river delta, Vietnam	Agricultural and food system	2015	t/year	3,89,346	1,44,191	2,45,154	(Tran and Weichgrebe 2020)
21		Miyun (Beijing), China	urban-agricultural system	2015	kg/year	55,05,420	27,99,505	27,05,915	(Cai et al. 2022)
22		Cleves, Germany	Agricultural and food system	2016	t/year	20,791	20,293	498	(Wiel et al. 2021)
23		Beijing, China	Urban Eco-system	2000–2016	Gg/year	530	395	66	(Pan et al. 2019)
24		Fujian Province, China	food system	2009–2019	kt/year	1297	1297	NA	(Xing et al. 2023)
25	Country	Finland	Food production and consumption system	1995–1999	t/year	2,76,500	2,23,500	53,000	(Antikainen et al. 2005)
26		Spain	specific treatment systems	1995–1999	t/year	26,900	22,440	4460	(Sokka et al. 2004)
27		Austria	Urban Eco-system	2001–2006	kg/person/year	41	35	NA	(Thaler et al. 2015)
28		Finland	Aquaculture system	2004–2007	t/year	829	81	748	(Asmala and Saikku 2010)
29		China	crop-livestock system	1980–2010	Tg/year	35.1	33.2	1.8	(Jin et al. 2021)
30		Beijing, China	Urban Eco-system	1996–2012	Gg/year	507	NA	NA	(Zhang et al. 2016)
31		China	Urban Eco-system	2014	Tg/year	103	77	27	(Luo et al. 2018)
32		Spain	Urban Eco-system	2016	kt/year	2142	969	913	(Mayor et al. 2023)
33		Sweden	Urban Eco-system	2016	t/year	268,000	98,200	170,000	(Sinha et al. 2022)

data in Table 4, details from two studies (selected due to the availability of data for all flows and stocks) are provided. Wiel et al. (2021) examined annual N flow in the whole agricultural and food system of district Cleves in Germany in 2021. Wiel et al. (2021) discovered that approximately 9% of the total amount of N that entered the study area in 2021 was stored within the system, specifically in soil (agricultural land) system and landfill (waste management). The main annual internal N flow was from food and feed processing to animal production unit (54% of total annual inflow). Approximately 8469 t/a N (41% of total annual inflow) and 1482 t/a N (7% of total annual inflows) were returned back into the agricultural

and food system as manure from animal production to crop production sector and as local animal product consumption from animal production to human consumption sector, respectively. A region scale study of N flow in Bang Pakong basin, Thailand, for animal production system (Kupkanchanakul and Kwonpongsagoon 2011) found that approximately 15% of the total N inflow was held in agricultural land and natural land as a stock. The main internal flows of N in this study were wastewater and solid waste flowing from consumption-related (animal production) process to waste-related process as 39% and 20% of total inflow, respectively (online resource Table

Table 4 Recycling flows of N at different geographical scales

Recycling flow (% of total inflow)	Sludge	Organic Municipal Solid Waste (MSW)	Compost/manure	Food	References
At region scale	–	5.26%	11.13%	–	(Do-Thu et al. 2011)
	–	7.50%	–	–	(Lederer et al. 2015)
	–	–	40.73%	7.13%	(Wiel et al. 2021)
	4.73%	–	–	–	(Kupkanchanakul and Kwonpongsagoon 2011)
	–	–	0.69%	–	(Coppens et al. 2016)
	1.74%	–	–	–	(Pan et al. 2019)
	3.91%	–	5.28%	20.55%	(Boh and Clark 2020)
At country scale	–	–	14.35%	–	(Luo et al. 2018)

A-3). Approximately 5% of total N inflow was returned back into the animal production system as sludge.

Key stocks at various geographical scales

A review of these studies found that a large fraction of the overall amount of N entering the system is stored as stocks at the city, region and country scales (Fig. 4). At the city-scale analyses, a significant proportion of the total N flow was found to be stored within the system only (Fig. 4a). At city scale, landfill has been determined as the primary source of N stock. At the city scale, N stock has been identified as landfill, soil for agriculture use, and Soakage Pit. N stock in landfill was found to be approximately 5% in Haiphong, Vietnam (Aramaki and Thuy 2010). However, in the case of St. Eustatius, Netherlands, Firmansyah et al. (2017) approximately 4% of the total N inflow was discovered to be stored in soakage pit. Based on findings of these studies, recovery of (N) from solid/liquid waste can significantly reduce chemical N fertilizer stock. According to our findings, recovering N from waste streams prior to landfill, as well as secondary recovering N from available landfill wastes and using it in agricultural sectors, can significantly minimize the input of chemical N fertilizer.

At the region scale, most of the studies indicate the retention of the significant portion of N inflow within the system, e.g. in five of the eighteen reviewed studies (Fig. 4b). Most of studies at this scale have found the soil in the ecosystem, soil for agricultural use and landfill to be the primary source of N stock. For example, approximately 17% of total N inflows in Central Arizona–Phoenix, USA (Baker et al. 2001), and 37% of total N inflows in Red river delta, Vietnam (Tran and Weichgrebe 2020), were found as stock in soil (ecosystem storage) and landfill (waste management). At the country-scale analyses, the total inflow of N was found to be stored within the system in three of the nine reviewed assessments, as shown in Fig. 4c. At the country scale, a significant portion of the total N inflow is retained in the soil in the ecosystem, soil for agricultural use, animal husbandry

and landfill. For example, approximately 6% and 9% of the total annual N inflow was stored in animal husbandry in Finland (Antikainen et al. 2005) and in Austria (Thaler et al. 2015), respectively.

At the city, region and country scales, higher emphasis should place on measuring the N stock in agricultural soils and waste going to landfill. Every year, a substantial amount of total N inflow is stored in the soil, either as ecosystem storage or in agricultural land. Utilizing N stores in this soil for crop production might decrease demand for chemical N fertilizer input, aiding in resource conservation (Amann et al. 2021; Aramaki and Thuy 2010; Asmala and Saikku 2010; Baker et al. 2007). Modification of plant species for increased N absorption and internal N use efficiency could also increase N recovery and contribute to the better N management goal (Garnett et al. 2009).

Key recycling flows at various geographical scales

The type and magnitude of the major N recycling flows at a particular geographical scale can be interpreted as an indicator of the scale's N management status. Higher recycling and recovery in a system indicate an efficient management of N flows. The analysis of the key N recycling flows at various geographical scales (Table 4) demonstrates that recycling flows account for just a minor share of total N inflow in the majority of the examined studies. Adoption of the total N recycling flow strategy was not found in any city-scale studies that were reviewed.

Total N recycling was found to account for less than 20% (weighted average) of total inflow at region scale in reviewed studies. As per findings from reviewed studies at this scale, the most important recycled flow is the flow as compost/manure export from animal production to crop production sector and food from animal production to human consumption sector. In a study from Thailand (Kupkanchanakul and Kwonpongsagoon 2011) and Beijing, China (Pan et al. 2019) sludge from waste management sector to the agriculture sector, accounting for approximately 5%, and 2% of the total

annual inflow in Bang Pakong basin, respectively. N recycling at the country scale was not considered in most of the studies. In a study from China, N recycling flow has been identified as compost/manure export from animal production to crop production sector, 14% of the total inflow for urban ecosystem (Luo et al. 2018).

This study demonstrates that the application of MFA is scale-independent, with the same methodology applicable to small and very large systems. The focus and methods, however, vary significantly depending on the scale. In general, region- and country-scale studies of MFAs need the work of several research groups from each of the countries that are taking part. It is important to get a complete set of data on the sink and sources with flows of N from agriculture, industry, trade and commerce, private households, water and wastewater management, and waste management. It is further essential to use the uniform method for collecting, calculating and evaluating the data. To ensure consistency in methodology, capacity building and knowledge transfer are implemented among all groups and participants.

Knowledge gaps and suggestions for goal-oriented decision-making in N management

Having reviewed studies on N flow at various geographical scales, some knowledge gaps have also emerged, e.g. city-scale studies have received the least attention among all the geographical scales. This may be simply because in terms of N flow, the regional scale is significantly more relevant than the city scale because it takes into consideration the agriculture (both crop and animal) production sector. Typically, a significant portion of N that enters at a country scale, whether as BNF or chemical fertilizer, is predominantly employed within the agricultural sector. Furthermore, the greater share of the N stock remains within the soil of this sector, and the primary outflow of N arises from either emission, soil losses through erosion, runoff, and leaching. Hence, in future examinations of N flow, it is essential to focus more on the regional scale that thoroughly considers this sector. This approach can uncover valuable insights, particularly in regions featuring large river systems like the Mekong or Ganges, and in areas where substantial international exports of human food and animal feed occur, as is the case with the Mekong Delta (Kupkanchanakul and Kwonpongsagoon 2011; Pharino et al. 2016; Pan et al. 2019). Moreover, country scale may sometimes be difficult to model because of being a very large system incorporating wide variety of processes and sectors and lack of data regarding interaction with other countries/regions. Furthermore, none of these studies consider the effects of land-use changes or climate change on N flows and stocks. The studies at regional scale can provide essential insights, but climate change may compromise the accuracy of these results

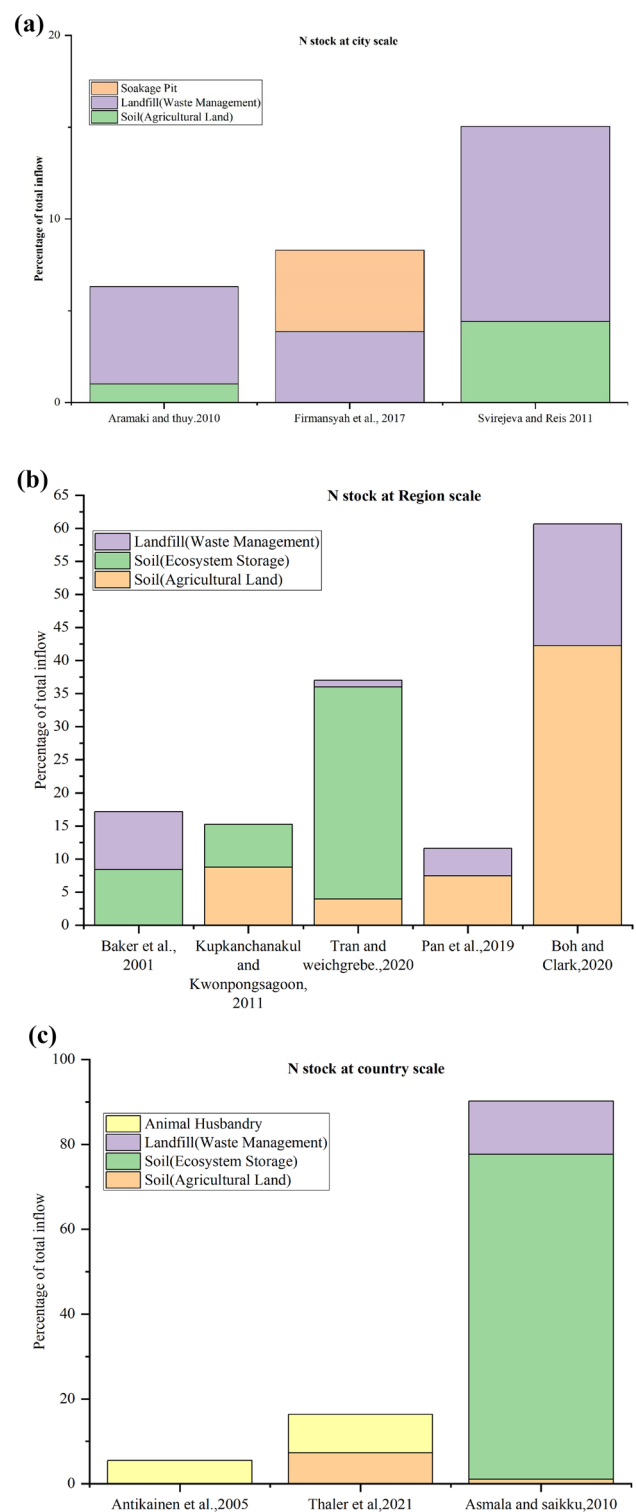


Fig. 4 Key N stocks at the **a** city, **b** region, and **c** country scale

over long-term assessment. The climate change can affect the availability and mobility of N in the soil, alter the patterns of precipitation and runoff, and change the temperature and humidity levels, which can all impact the N cycle. These

changes can lead to alterations in the N inflows, outflows, stocks, internal flows, and recycling flows, which can affect the accuracy of the results of long-term assessments (Mondal 2021).

The review of different studies for various geographical scales also revealed that most of them are examined for 1 year only. The majority of inferences in this study are based on the available literature that was conducted for one-year duration except for (Antikainen et al. 2005; Asmala and Sainku 2010; Jin et al. 2021; Pan et al. 2019; Sokka et al. 2004; Thaler et al. 2015; Xing et al. 2023; Zhang et al. 2016). Long-term changes in societal, political, economic and technological issues may take years to take effect. Large-scale natural activities such as erosion, floods, droughts and fire can all have a significant impact on the fate and volume of N flow. Moreover, it may take more than a year to return and consider variable natural processes to occur, especially at region and country scale. However, these factors can influence the nature and magnitude of N flows over time. In a region-scale study of N flow over 16 years (2000–2016) in Beijing, China, Pan et al. (2019), for example, discovered that various socioeconomic factors, such as modernization, increased living standards, and demographic change, are responsible for the increased intensity of N flows linked to emissions, fertilizer use, and waste generation, while lowering the N recycling ratio in wastes. Major challenge associated with multiple year N flow analysis could be the availability of high-quality data, particularly in developing countries. The organizations bearing responsibility for data collection may have data for a specific region or year but perhaps not for all regions or years, which may be one of the reasons why a multi-year study is not conducted. The problem associated with data quality and its availability, as well as its impacts on the results of the N flow assessment, has been studied by Amann et al. (2021). Hence, it is recommended that research laboratories and such other agencies should give priority to data collection of N flows, modifications and uses at various geographical and temporal scales.

The life-cycle approach, which requires detailed information about the inputs, outputs, and environmental impacts of each stage of a process, gives a clearer picture of environmental impacts of N management in any system. However, it was outside of the scope of this study. Again, it would be difficult to obtain comprehensive data for all the variables required for life-cycle assessment. Additionally, the availability and quality of data may vary between old and new studies, which could impact the comparability of the results. However, comparing old and new studies could provide insights into the changes in N flow over time and the effectiveness of N management policies and practices. Over longer time periods, minor inflows and stocks of N could have a significant influence on causing environmental damage and resource shortages. Therefore, it is important

to consider the impact of local policies and regulations on N management when analysing N flow over time. An initial assessment of these studies found a lack of quantitative information on various N flows, particularly in city- and region-scale studies.

The year when the study was conducted could matter in the N mass balance due to the impact of technological advancement over time, local policies and stringent environmental legislation on N management. To compare an old study to a new one, several aspects can be examined, including the research questions, methodology, data sources and findings. However, it is crucial to consider that the outcome of any N flow analysis is influenced by how the system is defined in terms of geographical scale and key sectors of N flow. This becomes particularly challenging when comparing studies that focus on different aspects or have varying system boundaries, especially when comparing studies conducted in developing and developed nations. The differences in socio-economic contexts, infrastructure, agricultural practices, and environmental policies between these two types of nations can significantly impact N flows, making direct comparisons complex. Careful consideration of these factors is necessary to ensure meaningful and valid comparisons between studies. In some studies, the focus is on specific defined systems for the entire geographical scale, rather than considering individual sectors. This approach can impact the findings of the study. This can lead to a potential oversimplification of the complex dynamics and interactions within the system. Therefore, it is important to carefully consider the inclusion of individual sectors and their specific contributions when conducting research to ensure a more comprehensive understanding of the subject and to avoid potential limitations in the findings.

This study focused on assessing the key N inflows, outflows, stocks, internal flows and recycling flows at the city, region and country scale. Present study primarily aimed to evaluate the interlinkages between sources and sinks of flows within a system using a percentage basis, rather than comparing these relationships with same or other geographical scales. This approach allowed us to gain insights into the relative importance of different sources and sinks within the same system and identify potential areas for improvement or intervention. The study did not examine N flows at the global or multi-country levels. The information obtained from this study can be used to make better N policy and management decisions for a city, region and country scale and to guide future research that aims to analyse N flow at different geographical scales.

Conclusions

This study reviewed the existing literature on nitrogen flow and compiled the geographical scale specific key N sink and sources with flows. The conclusions from the study are as follows:

- (i) The most important sectors for N flow are consumption-related (household; market; industry; livestock; animal husbandry), atmosphere (deposition and emission), waste-related (solid waste; waste water; landfill; composting; incineration; onsite sanitation systems), soil-related (agricultural soil; forest soil; crop production) and water-related (surface water; ground water; ocean; river; canal) considering all the geographical scales.
- (ii) The important flows are exchange with water- or soil-related sector (water; wastewater; leaching; runoff; erosion), exchange with atmosphere (emission; BNF; deposition on soil) and agriculture (chemical fertilizer; manure export).
- (iii) At the city scale, N enters the system primarily as human food, miscellaneous (e.g. fossil fuel) flow and exits primarily as emission to atmosphere, soil losses, exported food and wastewater. Most of the N stocks at this scale occurs in landfill and soil used for agricultural use.
- (iv) At the region scale, the primary inflow of N is: feed, fertilizer, BNF, and food, while the primary outflow is emission to atmosphere and exported food. Most of the N stock occurs in soil available in ecosystem, soil used for agricultural use, and landfill.
- (v) At the country scale, the most of N imports come from feed, fertilizer, BNF and deposition, while the most of N outflows occur through emission to atmosphere, exported food and soil losses. The vast majority of N stocks at this scale are held in soil available in ecosystem, soil used for agricultural use, and animal husbandry.
- (vi) N recycling flows were discovered to be nearly or less than 20% of total inflow in most of the studies at various geographical scales.

The findings from this study can be very useful for future studies on N flow in achieving efficient N management at any geographical scale. N studies conducted using these findings can be used as a starting point for developing policies and guidelines aimed at achieving N sustainability in any region. Future scope may include collecting data over several years for systems at city and region scale. It may also consider the effects of land use change and climate change on flows of Nitrogen.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10098-023-02637-6>.

Author contributions Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation – Shubham Rana, Amit Kumar Supervision, Validation, Writing- Reviewing and Editing - Amit Kumar, Nand Kumar and Mahesh Kumar Jat.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare no conflict of interest.

Ethical approval The manuscript has not been submitted to more than one journal for simultaneous consideration.

Consent to participate This study has not directly/indirectly involved human and/or animals.

Consent for publication The manuscript was reviewed, and all authors consented to publish.

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