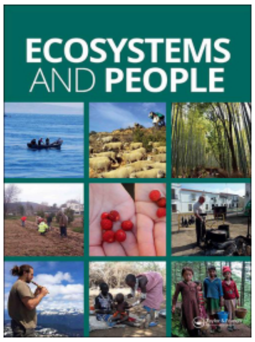

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Exploring human-nature relationships in academic literature on the nitrogen cycle

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ABSTRACT
The nitrogen (N) cycle is a familiar concept. As is the much simplified, often diagrammatic, representation commonly used to illustrate the scale, importance and interconnectedness of this global cycle that links air, water, rocks and living beings. However, in this representation, humans are often presented as a seemingly minor entity or not explicitly shown at all. This can obscure the idea that humanity is both a direct beneficiary of the nitrogen cycle (through food and resources) and an increasingly significant influence on its function. This study sought to understand how diverse Human-Nature relationships (HNR) are expressed in recent academic literature on the nitrogen cycle. A sample of peer-reviewed literature, containing explicit and inferred examples of HNR and the nitrogen cycle, was analysed using two approaches: 1) network analysis, identifying and illustrating all quantifiable links made between components of the nitrogen cycle, and 2) content analysis to understand how different kinds of terminology were being used to describe relationships between components in the cycle. The network analysis revealed diverse links between 'human' and 'non-human nature'. The content analysis found some explicit use of relational terms, most commonly 'depend*'. Both approaches highlighted strongly reciprocal links within the 'human' realm and the explicit centrality in which this is held across the corpus. We demonstrate the utility of combining quantitative and qualitative analysis to understand nuanced relationships in the nitrogen cycle and explore the utility this has to increase the acknowledgement and appreciation of HNR in science communication and science-policy interface work.

KEY POLICY HIGHLIGHTS

- A network analysis of nitrogen flows empirically quantified in the scientific literature showed a prominence of human components in the nitrogen cycle and how they are connected to different atmospheric, aquatic and terrestrial non-human components.
- A qualitative content analysis of the same scientific literature also showed the prominent role of human activities within the nitrogen cycle, while revealing a wide acknowledgement of relationships between humans and non-human nature.
- Integrated knowledge on the strength and nature of those relationships is still needed to better inform policy.
- Our mixed approach can be applied for other biogeochemical cycles that are key for global ecosystem functioning.

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1. Introduction

The growth and industrialisation of human societies have provided numerous social benefits but also come at a profound cost to the environment. The currently dominant, Western conceptualised, paths of development which focus on economic growth are driving climate change and global declines in biodiversity, which in turn risk eroding our own quality of life (IPBES 2019). The prevalent view in science and society, historically aligned with this economic growth model, tends to characterise humans – the species *Homo sapiens sapiens* – and human activity as separate from all other parts of the earth system (Caillon et al. 2017; West et al. 2020). There are growing arguments that this view: (i) inadequately describes humanity's position within the biosphere, (ii) represents a narrow, albeit prevalent and influential, Western worldview, and (iii) ultimately underpins the environmental crises that we now face (Van Schyndel Kasper 2008; Caillon et al. 2017; Muradian and Gómez-Baggethun 2021). Fundamentally changing this view is, arguably, critical for achieving transformative change towards sustainability (Wyborn et al. 2020).

In this study we address the question of how the relationship between 'humans' and 'non-human nature' is represented in recent academic literature on the nitrogen cycle. We assess: 1) to which extent 'humans' and 'non-humans' are treated as distinct or related entities, and (2) the nuance and consistency in the ways these relationships are presented and described in relation to the nitrogen cycle.

1.1. Importance of biogeochemical cycles and nitrogen

Biogeochemical cycles, including the carbon, nitrogen, phosphorus, and water cycles, play a fundamental role in regulating Earth's biogeochemical dynamics and sustaining ecosystem functioning (Stein and Klotz 2016; Schlesinger and Bernhardt 2020). These cycles drive the flow of essential elements and nutrients through various environmental components, including the atmosphere, lithosphere, hydrosphere, and biosphere. The interconnected biochemical cycles form the basis of Earth's life-support systems, influencing key ecological processes such as primary production, nutrient cycling, and energy flow (Chapin et al. 2011). Disruptions – whether induced by natural phenomena or human activities – in one cycle can cascade throughout ecosystems and have far-reaching consequences, impacting ecosystem structure and function, biodiversity, and the provision of crucial ecosystem services such as food production, water purification, and climate regulation (Chapin et al. 2011; Schlesinger and Bernhardt 2020). Understanding these mechanisms and feedbacks within those cycles is necessary to explain ecosystem responses to environmental change and inform decision making in the face of global challenges such as climate change and biodiversity loss (Schimel et al. 2015).

Nitrogen is arguably the most important nutrient in regulating primary productivity and species diversity in both aquatic and terrestrial ecosystems (Vitousek et al. 2002), therefore playing a major role in regulating the functioning of the Earth System. The bulk of this nitrogen arises from microbially-driven or industrial processes such as nitrogen fixation, nitrification and denitrification, which make up the nitrogen cycle (Bernhard 2010) (and see SI-1, Figure 1). The global nitrogen cycle has been heavily disrupted by human activity (Vitousek et al. 1997; Galloway et al. 2008; Melillo 2021), and there is evidence that its 'planetary boundary' – beyond which the functioning of the Earth System may be substantially altered – has been exceeded (Rockström et al. 2009, 2023; Steffen et al. 2015). Particularly in Europe, there are comprehensive studies that assessed the impact of human activities on nitrogen fluxes and the environment (Sutton et al. 2011). Unless further action is taken, population increase, exacerbated energy use and unsustainable use or consumption of animal products (unsustainable diets) could further increase nitrogen nutrient losses, pollution and land degradation, putting additional pressure on the quality of our water, air and soils (Sutton et al. 2013 Pg. vii). This is associated with considerable biodiversity losses and social costs (Keeler et al. 2016).

1.2. The concept of human-nature relationships (HNR)

In his formative book on the topic ('People and Nature: An Introduction to Human Ecological Relations'), Moran (2006, Pg. 8) explains that: 'the Cartesian dichotomy between humans and nature is a peculiar notion in Western society that is not widely shared cross-culturally. Most people in the world do not externalize nature in this manner'. Given the growing dominance of this view, he goes on to claim that: 'one of the challenges before us in contemporary society is how to re-conceptualize the interactions between people and nature'. Many have rallied to this challenge. Nonetheless, the Western view of the world, also dominant in contemporary academic literature, remains dualistic (with 'humans' and 'non-human nature' as two distinct entities), utilitarian (focusing on the value of 'non-human nature' for humans) and anthropocentric (with humans as the most important element of existence) (West et al. 2020; Muradian and Gómez-Baggethun 2021).

The 'ecosystem services' (ES) concept (describing benefits that humans directly or indirectly receive from ecosystems (Millennium Ecosystem Assessment 2003; Dick et al. 2011)) which has a strong influence on environmental decision-making is: 'situated quite clearly in the nexus of anthropocentric and utilitarian dimensions of human – nature relationships with notions of nature as separate from humans, though more inclusion of cultural perspectives and intrinsic values are emerging' (Flint et al. 2013, p. 208). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has attempted (IPBES 2019) to reduce the utilitarian focus of ES, developing the 'nature's contributions to people' (NCP) paradigm, which acknowledges nature's wider provision to people and its role in cultures inclusive of indigenous and local knowledge (Díaz et al. 2018; Kadykalo et al. 2019). But both ES and NCP maintain the dichotomous separation between 'humans' and 'non-human nature'.[1] To go beyond the two concepts, Muradian and Gómez-Baggethun (2021, p. 1) in their critique of ES and NCP propose 'a shift from a morality of utility to a morality of care, a reallocation of property rights, and the extension of the community of justice to non-human entities'. West et al. (2020) have also argued for a 'relational turn' that can better capture the complexity of human-nature connectedness. 'Social-ecological systems' (Young et al. 2006; Ostrom 2009) and other coupled human-environment system concepts (Turner et al. 2003) are also being iterated to provide a more holistic and less dichotomous perspective for research and decision-making (Fischer et al. 2015). Raymond et al. (2021, p. 1) argue that 'researchers inevitably need to make strategic choices about how to divide system components if the goal is to systematically assess relations and to promote transformations toward sustainability'. The way in which we divide and explain system components is important, as these then form the visual and textual means in which HNR are communicated and our attitudes can be strongly influenced by stories and narratives we are surrounded by (Fisher 1984). These concepts increasingly aim to disrupt the idea of separation between 'humans' and 'non-human nature', by acknowledging the artificial distinction between different lived experiences, knowledge types, academic disciplines, and economic sectors that this separation requires.

1.3. Human-nature relationships in the nitrogen cycle

Exploring the relationships between human activities and biogeochemical cycles is crucial, since human activities have become major drivers of environmental change, significantly altering natural processes (Vitousek et al. 2019). The nitrogen cycle is familiar to many people, both in academia and in pre-university education, as it is often part of foundational science education, presented as a relatively simple 'food-web style' network that aims to explain the complex interactions of species, cycles and processes (e.g. Britannica 2023). This convention of simplification means that such networks do not sufficiently communicate the broad direct and indirect influences of, and consequences for, humans and non-human nature (Compton et al. 2011), but are often perpetuated, including in decision-making contexts e.g. European Environment Agency (n.d.) and OECD (2018). While simplification is necessary to achieve clear communication of the overall nature of something as complex as a global biogeochemical cycle, overly simplified views can be detrimental to communicating and understanding the system in a holistic way. Understanding these interactions allows us to predict and mitigate the negative impacts on ecosystem health and human well-being.

This study sought to explore the ways in which the components, flows and relationships within the nitrogen cycle are represented (both quantitatively and qualitatively) in published academic literature. As noted above, the nitrogen cycle provides a useful case study because of: (i) the importance of nitrogen as a life-supporting nutrient; (ii) the level of disruption of the global nitrogen cycle due to human actions; (iii) the familiarity of the nitrogen cycle to many people; (iv) the fact that the nitrogen cycle has been thoroughly studied. Our research aims at enhancing our understanding of how HNR are framed, and potentially contribute to shifting attitudes in public and policy discussions towards acknowledgment of HNR and 'human' dependence on 'non-human nature'.

2. Materials & methods

We defined a set of key terms and their conceptual relationship, which were used to frame the study (Section 2.1). Then, we carried out a structured literature search and analysed how HNR have been reflected in a representative sample of the academic literature related to the nitrogen cycle, as described in Section 2.2. Using the identified body of literature, we:

1) Conducted a network analysis of linkages among components of the nitrogen cycle, based on studies where nitrogen flows were quantified with empirical data (Section 2.3.1). Specifically, we compiled data-supported linkages between predefined 'human' and 'non-human nature/natural' (biotic or abiotic) components.

2) Carried out a content analysis to explore how HNR have been portrayed semantically. We coded key terms indicating HNR and explored the ways in which these terms were used within the contexts of the papers. (see Section 2.3.2).

2.1. Conceptual approach

There is varied interpretation of different 'relational' terms in previous work in environment and ecology and increasingly rich theory and practice around 'relational values' (Muradian and Pascual 2018; Saxena et al. 2018; IPBES 2022). Therefore, we co-developed a glossary and conceptual figure to summarise our own understandings and assumptions in relation to this study. A preliminary review of papers identified by the project team as key texts in the field (recent, topically relevant, highly cited) (see test set of key papers SI-2) highlighted the likely prevalence of 'dependence' and allied terms (dependency, interdependence) and to a lesser extent 'connection' and 'relation' (connection, interconnection, relationship, interrelationship). These are defined in SI-3, Table 1 which combines dictionary definitions and definitions from sources including the IPCC and IPBES Glossaries (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, I 2022; IPCC 2023). SI-3, Table 1 also contains definitions of some framing terms that we use consistently throughout this study (e.g. nature, human systems, social-ecological systems).

Figure 1 shows a conceptualisation of linkages between nodes labelled with letters A to E. The following assumptions were used: i) Dependence can be 'direct' or 'indirect'; ii) not all things that are 'dependent' are 'interdependent' i.e. only some relationships are bidirectional (reciprocal); iii) many things are 'interconnected', but the exact nature of these relationship is diverse. Using such a hypothetical system with a set of unidirectional and bidirectional connections among ecological (green) and social (yellow) nodes it is possible to determine direct and indirect (inter-)dependent interactions. By linking two or more direct interactions together, interaction chains with potential indirect interactions occur (Wootton 2002). For example, in the chain A → D → E, E is indirectly dependent on A via direct dependence on D. In this conceptualisation, social node C is also directly dependent on ecological node A but could itself indirectly influence A via the direct reciprocal interdependence chain C↔B↔A. In this way, complex

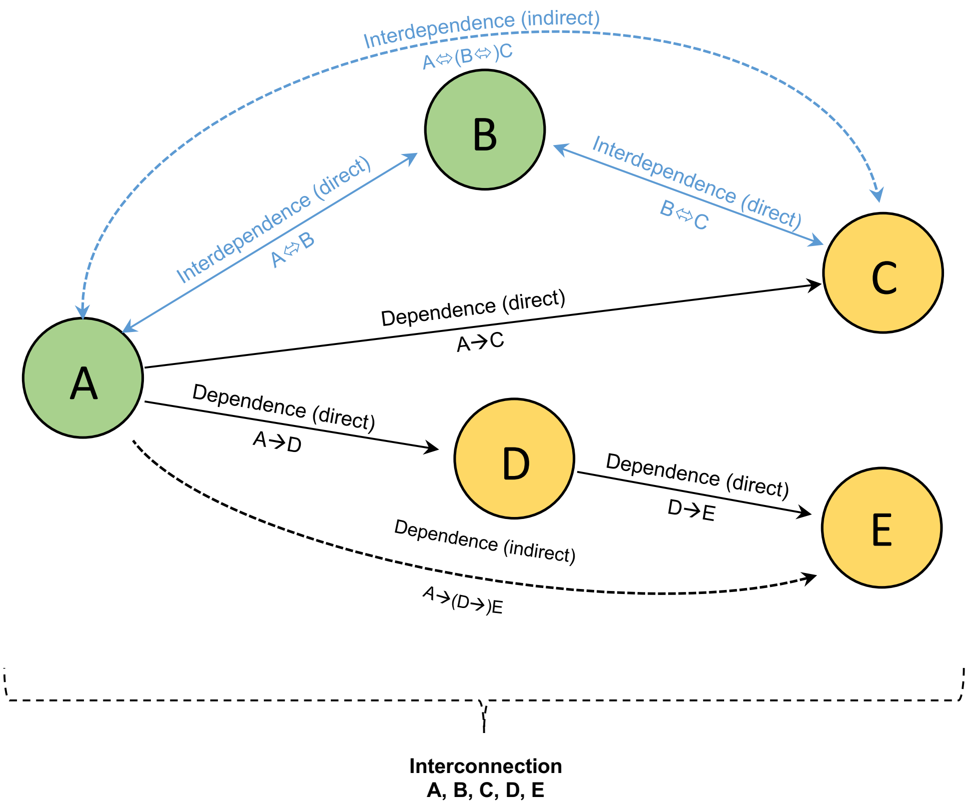

Figure 1. Illustration of key terms used in our analysis to describe interconnection and dependency pathways. Definitions: i) Dependence: the conditionality of any component of the biosphere needing interaction with other biosphere component(s) to sustain its existence; ii) Interdependence: the conditionality of any components of the biosphere requiring interaction(s) with each other to sustain their existence. Used more often to indicate complex and/or reciprocal relationships; iii) (inter)connection: the state of having different parts or things connected or related to each other.

Table 1. Realms, nodes and node definitions used in the network analysis based on Galloway et al. (2008) and Gruber and Galloway (2008).

Realm	Nodes	Definition
Aquatic	Terrestrial water biota (TWB)	All living things within terrestrial water bodies (lakes, rivers streams, ponds, winterbournes, wetlands (freshwater)).
	Abiotic terrestrial water (ATW)	The non-living component of land-based water bodies which are as for TWB (see row above)).
	Marine water biota (MWB)	All living things within marine water bodies, inc. estuaries and saline water coastal environments e.g. salt marsh water bodies.
	Abiotic marine water (AMW)	The non-living component of marine water bodies.
	Marine sediment (MS)	Water-based pool of buried nitrogen (e.g. in the soil or deep sea or sub-benthic) that ends up or is in sediments.
Atmosphere	Atmosphere (AT)	The entirety of, and composition of the earth's atmosphere. Anthropogenic emissions would be represented by: FFE→AT; compositional change would then be in the AT domain.
Terrestrial	Soil/Lithosphere (SL)	The lithosphere, soil as a habitat, resource and physical entity; land or terrestrially based, the non-human component of soil (outside or deeper than agriculture). It includes the rhizosphere and its microbial processes.
	Terrestrial biota (TB)	All living things on land (excluding humans, as well as vegetation and animals within human production systems (crops, livestock and aquaculture)).
Human	Crop cultivation process (CC)	Represents the cultivation process (incl. irrigation on 'arable soils', effects of the fertilisation process) and production of plants (incl. food crops, feed/forage crops, cash crops, green manure crops, straws and hays, horticulture, lawns) e.g. Industrial fertiliser use within crop production is IN → CC but the N fertiliser effects on soil microbial processes would be CC → SL. Grasslands used to produce indirect fodder (hay or silage etc.) are considered to be within CC e.g. hay may pass through a market (HSE) before getting to livestock (LA).
	Livestock and aquaculture (LA)	Represents activities that raise animals incl. pelt animals and horses to provide animal products; incl. unused excreta (both liquid and solid parts excreted from animals) but if recycled as manure/organic fertiliser it becomes a link to CC); incl. (recycled) by-products; incl. managed grasslands (e.g. fertilised) where they are used as direct feed by livestock; impacts of fishing actions as waste dumping.
	Fossil fuels and energy (FFE)	Represents transport of goods/feed/food & energy production (incl. burning wood, hydroelectric nitrogen production, etc.) for industrial processes (mining industry; raw materials industry; the food, feed, chemical materials processing industry; processing industries etc.)
	Industrial N incl. chemical fertiliser (IN)	Represents the creation of mineral nitrogen (e.g. Haber-Bosch artificial nitrogen fixation process, the main industrial procedure for chemical fertilisers).
	Human consumption and waste (HCW)	Human consumption not only for sustenance but also other consumption involving nitrogen e.g. explosives or gas propellants; waste includes the treatment of industrial wastewater, domestic sewage, food garbage, landfills.
	Humanity, society and economics (HSE)	Human biomass and all remaining human activities, including societal, economic and health-based activities but excl. natural resource use, industrial processes and consumption.

interconnection and dependency pathways can occur. Due to this complexity, indirect connections (depicted as dashed arrows) are not further analysed in the following chapters.

2.2. Literature search and selection

Given the vast extent of literature about the nitrogen cycle, we carried out a structured and representative (non-exhaustive, non-systematic) review (Figure 2). We developed a search string, guided by the research question ('How is the relationship between "humans" and "non-human nature" represented in published scientific literature on the nitrogen cycle?') and the defined keywords (SI-3, Table 1) used throughout this study. We searched for literature using the Web of Science Core Collection (WoS; www.webofscience.com.) and Scopus® database (www.scopus.com). We considered peer-reviewed journal articles published in English between January 1970 and December 2021.

We wanted to be sure that papers in the final corpus included a variety of nitrogen cycle components, and that we did not only identify papers likely to validate our assumptions. We developed blocks of search terms covering four major domains that we identified to be important through preliminary reading (see test set of key papers, SI-1):

- Domain that captures the nitrogen cycle;
  'nitrogen cycle' OR 'N cycle' OR 'N cycling' OR 'nitrogen cycling'
- Biophysical domain involved in the nitrogen cycle;
  'natur*' OR 'environment*' OR 'atmospher*' OR 'land' OR 'water'
- Social Domain related to humanity or anthropogenic impact;
  'human*' OR 'anthropo*'
- Domain of connections between human and non-human nature (relational);
  'connect*' OR 'interconnect*' OR 'depend*' OR 'interdepend*' OR 'cascad*' OR 'link*' OR 'interact*' OR 'feedback' OR 'flow*'

These blocks were developed by testing them against the test set of key papers (SI-2). To form the overall search string, these blocks were combined with the Boolean operator 'AND'. Test searches demonstrated that the separation of these domains and the aggregated keywords was essential and resulted in more relevant records. As noted in Section 4 (Limitations of the Study and Further

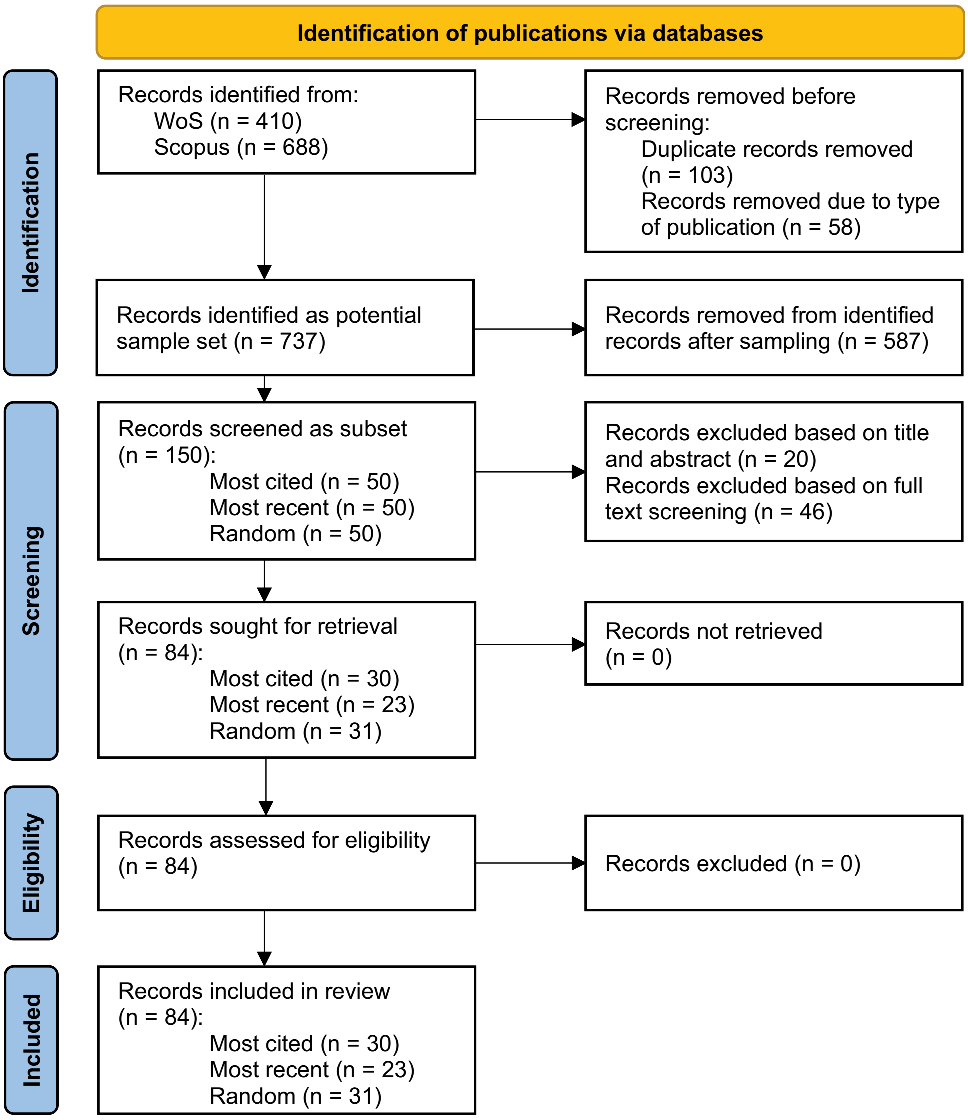

Figure 2. Flow chart for selecting literature for review. Modified from Page et al. (2021).

Work) we acknowledge the impossibility of capturing all possible relational terms but believe that this approach allowed the review to focus on a prevalent set of relevant terms.

The literature search using both WoS and Scopus® identified 737 articles. Full records of the search string were downloaded as individual BibTex files and joined in the R statistical software environment (R Core Team 2022) using the '*bibliometrix*' package (Aria and Cuccurullo 2017). We then added any key papers (SI-2, see Section 2.2) that were not returned in the search. After removing duplicates and adding relevant records, 655 records remained for further analysis (Figure 2). From this pool, 150 articles were chosen (50 most recent, 50 most cited, 50 random). This sub-sampling method of the initial corpus has been done by other authors (e.g. Scowen et al. 2021) and led to a representative and manageable number of papers. We then screened articles' titles, abstracts, and full texts. We adopted the following inclusion criteria: i) the article needed to define any type of interaction between human and non-human components of the nitrogen cycle, based on empirical data of nitrogen flows (excluding articles that defined only conceptual linkages) and, ii) the scale of the study had to be beyond the scale of the individual organism. Thus, medicinal, chemical or any type of study that exclusively involves laboratory, *in vitro* or other closed systems were excluded. We also excluded modelling studies that only refer to theoretical (e.g. statistical only) rather than measurable flows of nitrogen. Through this process, we identified 84 articles as relevant. These can be found in SI-4, where the metadata provides a summary of the topics covered by the studies.

2.3. Literature analysis

To examine the selected corpus of literature, we used two analytic approaches. Firstly, we conducted a network analysis, reflecting links among and between 'human' and 'non-human nature' components of the nitrogen cycle, quantified in the literature with measurable indicators. Then, we conducted a content analysis focussed on the semantic use of HNR in the analysed articles. For the selected literature, therefore, the following information was extracted from all papers: the general metadata of the publication (see SI-4), the nitrogen cycle-specific data (e.g. visualisation, domain); and the nodes and links between the different components of the nitrogen cycle (see 2.3.1). Qualitative descriptions of the nodes and links were then extracted where present (see 2.3.2).

2.3.1. Network analysis

We used a network approach to represent the conceptual relationships between different components of the nitrogen cycle. Network analysis is a method for investigating relational structures and processes (Janssen et al. 2006). A given system is represented and analysed as a set of nodes and the various types of relationships between them as links. Thus, network studies focus on a) relationships and b) how relationship patterns or structures affect processes and outcomes (Sayles et al. 2019). Janssen et al. (2006) proposed that network analysis could be an effective way to conceptualise and analyse not only social or ecological systems but also complex social-ecological systems. In these social-ecological networks, which represent society, the environment, and their relations, both social (human-related) and ecological (non-human related) components can be symbolised as nodes (Bodin et al. 2019; Sayles et al. 2019; Felipe-Lucia et al. 2022; Kluger et al. 2020). The diverse and multiple ways in which people and ecosystems interact create complex patterns of unidirectional and bidirectional (or reciprocal) interconnections (links) within and between social and ecological nodes.

For the network analysis, we decomposed the links between all components and characterised them based on the point of origin and endpoint of the link. We created the nodes based on the work from Galloway et al. (2008) and Gruber and Galloway (2008) since both papers are considered seminal, central works in the field of nitrogen cycling (highly cited and cross-referenced), and therefore a good starting point for defining the nodes. Those authors refer to nitrogen losses (to air, water, and land) and nitrogen atoms cascading through the environment and contributing to environmental responses. Based on these papers, nodes were created to ensure the network captures all the realms of the global nitrogen biogeochemical cycle, 14 nodes were included in the construction of the network (Table 1). Preliminary review results were checked by more than one reviewer to reduce disparities in interpretation between reviewers. This process was repeated until reviewers achieved congruent results from reviewing the same papers (same nodes linked).

Having defined the expected nodes of the network (Table 1), papers were screened for quantitative data to explore if and how these nodes and the links between them were quantified. We manually searched for quoted values in the text or figures of the papers that denoted the movement of nitrogen from one node to another, or within a node. Two conditions often prevented the inclusion of a link: either data referred to a nitrogen pool, thus not defining the movement of nitrogen, or the transfer of nitrogen values lacked a clear source or sink.

Papers were included in the final screening for use in network construction if they described at least a single link between nodes, e.g. a table or figure showing a measured flow, or text describing a flow with an empirical value associated. We did not count the number of linkages per paper or weigh them by the data values, as the literature was so diverse it would cause dilution of meaning and require a different set of definitions for every data type used. Each link between a node is therefore representative of counting an evidenced link, not counting the number of times the link was measured or described in a literature piece. In reference to Figure 1 (our conceptualisation of interconnection and dependency pathways) while we attempted to include indirect links in the network analysis, this was not possible because indirect links could not be accounted for without making subjective assumptions outside the nitrogen flow data being assessed. We did, however, achieve representation of 'A → D → E' style indirect links from the gathered data (see Figure 1).

Based on the linkages identified, we built a network of nodes and links among 'human' and 'non-human nature' components of the nitrogen cycle, using the R package '*igraph*' (Csardi and Nepusz 2006) version 1.3.5 running under R version 4.2.0 (R Core Team 2022). It is a directed network with weighted links between nodes (different N 'compartments'). The weight of each link is given by the number of publications reviewed which have quantitatively determined that link. All network representations are based on the Fruchterman-Reingold layout (Fruchterman and Reingold 1991), which places nodes on the plane using a force-directed layout algorithm. It is possible to have loops in the network (a link from a node to itself). The size of each node is proportional to its strength (total weighted number of in- and out-going links). For the analysis, besides the visual interpretation of the network we used some common metrics for network analysis, both at network and node level. At network level, we checked if the resulting networks were connected (every node is reachable from every other), network density (frequency of observed links relative to number of potential links – those that would exist in a network where all nodes are linked to each other), and network reciprocity (proportion of mutual connections in a directed network). Node centrality metrics included strength, in- and out-degree (Kolaczyk and Csárdi 2014). The final networks created are representations of the links identified in each reviewed paper, aggregated together for all papers.

2.3.2. Content analysis

Regardless of the number of nodes included in each paper, the content analysis provided a way to qualitatively explore described relations in the reviewed literature. We imported the full-text PDFs of the final corpus generated and processed in 2.3.1 into NVivo (NVivo 12 for Mac, QSR International Pty Ltd n.d.) and ran Text Search Queries (within the full documents) using the built-in query functions to identify the incidence of key relational terms based on the stems used in the search string block of 'connections between human and non-human nature' ('connect*' OR 'interconnect*' OR 'depend*' OR 'interdepend*' OR 'cascad*' OR 'link*' OR 'interact*' OR 'feedback' OR 'flow*'). Terms were automatically coded as nodes within the documents. The nodes were then manually cross-checked and verified, and retained only in cases where terms were judged by two reviewers to be used within a meaningful context with respect to HNR and the nitrogen cycle. The relational terms from the search string for which meaningful contexts were identified were: interconnec*, depend* and interdep*. To determine whether additional relational terms would be meaningfully present in the corpus, the generic relational term 'relat*' was also coded and three further additional (non-search string or project glossary) terms were explored: affect, impact* and influence.

Any relevant passages containing key relational terms from the search string were manually cross-coded into HNR nodes: 'human<>human' (where any interactions described were between nodes in the 'human' realm of the system as described in Table 1), 'nature<>nature' (where any interactions described were between nodes in any of the other realms of the system as described in Table 1), 'nature depend on human' (in which the authors used 'dependency' language to describe the relationship of nodes in any of the other realms with those in the 'human'), 'human depend on nature' (in which the authors used 'dependency' language to describe the relationship of elements of the 'human' realm with any of the other realms). Full quotes are recorded for illustrative purposes. Quotes were checked by more than one reviewer to reduce disparities in interpretation between reviewers.

3. Results and discussion

Table 2 gives an overview of the corpus of literature we reviewed. A list of all papers in the final review can be seen in SI-7. The complete corpus of literature has been cited more than 21,000 times and defined 130 flows of nitrogen. The total number of nitrogen flows is rather similar across the literature sub-samples. The random sub-sample covers the whole temporal period of the full corpus. In the following sections we focus firstly on the network analysis, then on the content analysis, then present a summary of key findings.

3.1. Network analysis

We developed three different network representations of the linkages between nitrogen components (nodes in Table 1): one providing a broad overview by aggregating nodes at the realm-level (aquatic, terrestrial, atmospheric and human realms in Figure 3); one showing the linkages between nodes considering the full literature corpus (Figure 4); and another one breaking down the full network into each sub-sample of article types used to build the corpus (most cited, most recent, random; Figure 5). Overall, the aggregated network at realm-level shows that all realms are inter-connected (network reciprocity = 1), with a predominance of the human realm, not only in relation to the other realms, but most notably within itself (represented by the loop arrow in Figure 3). This illustrates the explicitly quantified recognition of and focus on the significance of humans as part of the nitrogen cycle within the corpus (e.g. Galloway et al. 2008; Fowler et al. 2013).

Figure 4 illustrates nodes and links for the full corpus of analysed papers (node statistics for this network are given in SI-5). All nodes are connected to at least one other node and the network is a connected graph – every node is reachable from every other (Kolaczyk and Csárdi 2014).

Table 2. Summary table of the reviewed corpus of literature.

Corpus domain (no. of papers)	Total no. of citations	Average no. of citations	Year range	Total no. of flows
All (84)	21867	260	1976–2021	130
Most cited (30)	16324	544	1997–2019	92
Most recent (23)	96	4	2021–2021	81
Random (31)	5447	182	1976–2021	84

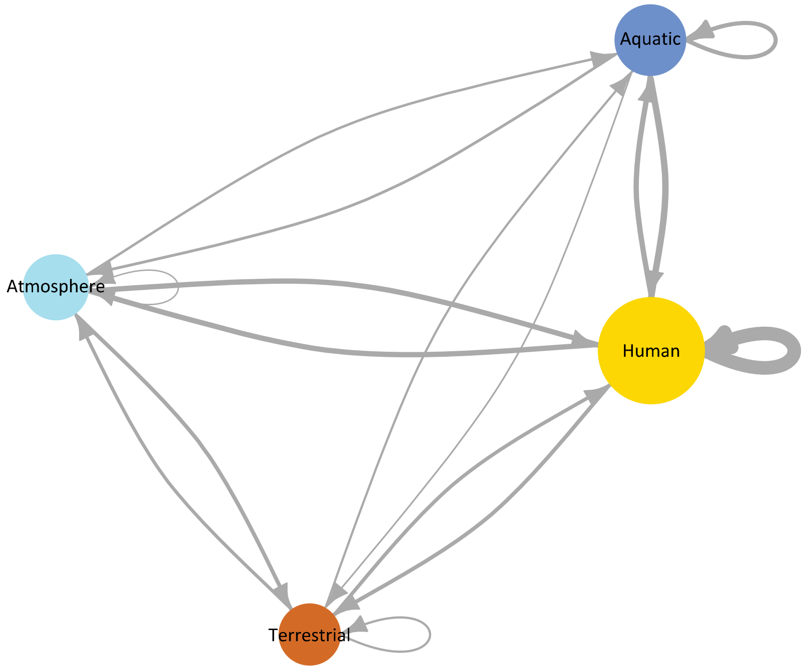

Figure 3. Network with nitrogen components aggregated at the realm-level, representing the full corpus of articles ($n = 84$). The size of each node is proportional to its strength (total weighted number of in- and outgoing links). The weight of each link is given by the number of publications reviewed which (quantitatively) define that link. Network layout (relative position of nodes) was automatically optimized by *igraph* according to Fruchterman-Reingold method.

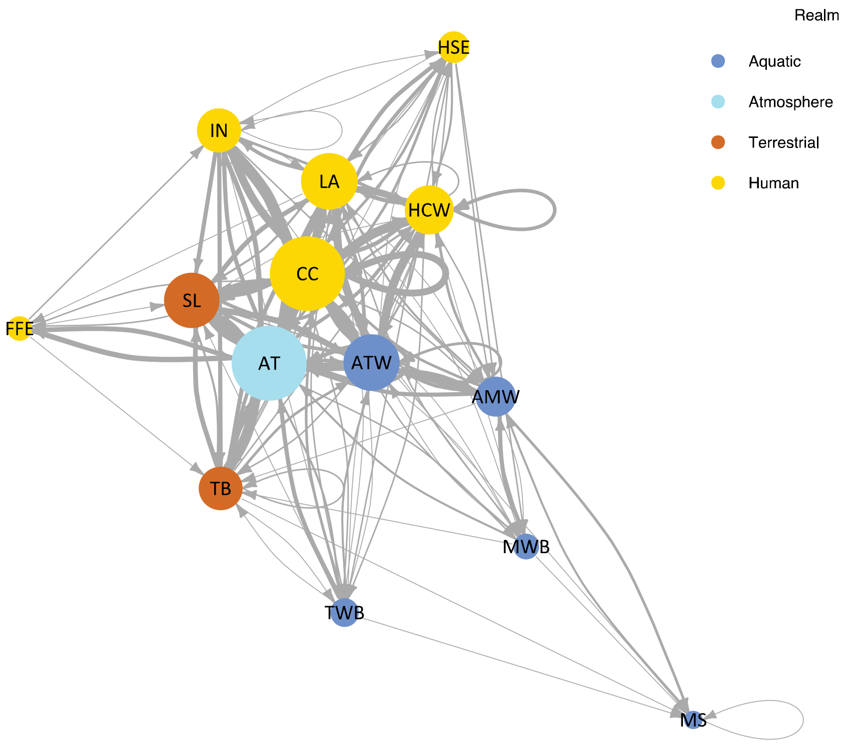

Figure 4. N-Network of nodes and links among human and non-human components of the nitrogen cycle, representing the full corpus of articles ($n = 84$). Nodes are as defined in Table 1: TWB – Terrestrial water biota; ATW – Abiotic terrestrial water; MWB – Marine water biota; AMW – Abiotic marine water; at – Atmosphere; MS – Marine sediment; SL – Soil/Lithosphere; TB – Terrestrial biota; CC – Crop cultivation; LA – Livestock & Aquaculture; FFE – Fossil fuels & Energy; IN – Industrial nitrogen incl. chemical fertiliser; HCW – Human consumption & Waste; HSE – Humanity society and economics. Network layout (relative position of nodes) was automatically optimized by *igraph* according to Fruchterman-Reingold method.

Nevertheless, the network density (representing the number of links as a proportion of the number of possible links) is 0,66, which means that the network has 66% of the links that would exist in a network where all nodes are linked to each other. The reciprocity of the network, which defines the proportion of mutual connections the extent to which there is reciprocation among links in a directed network

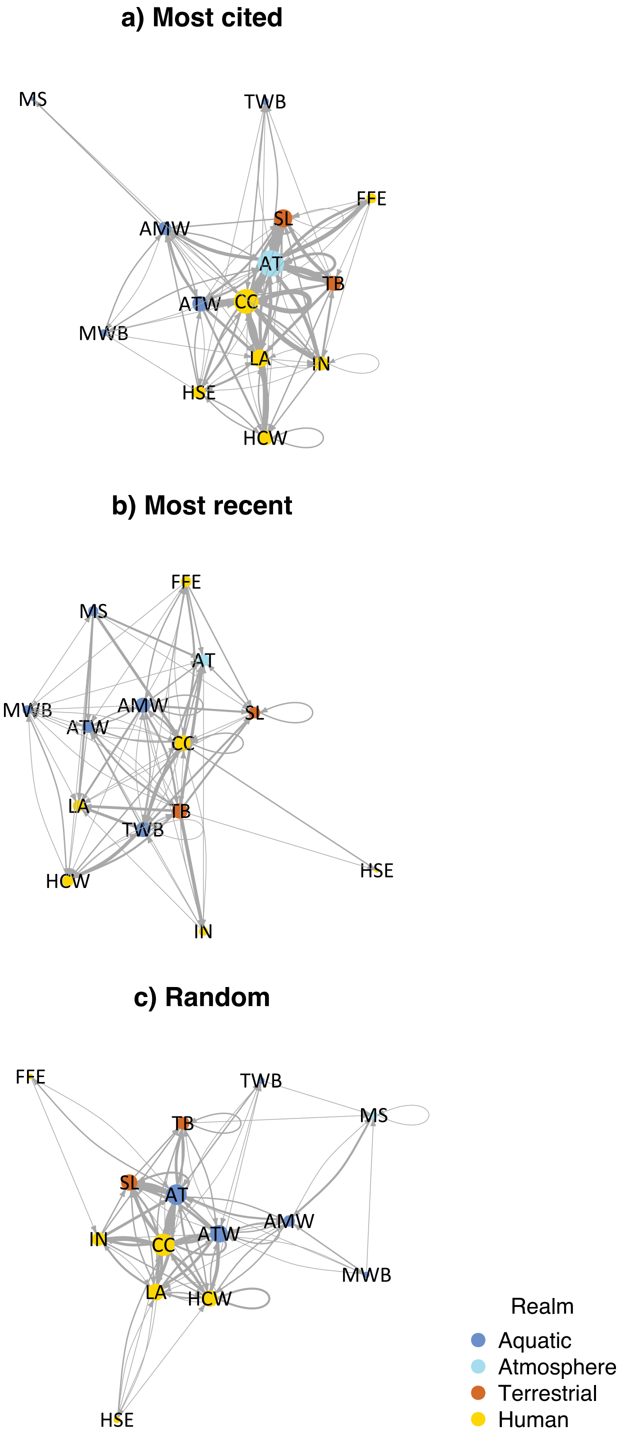

Figure 5. N-Network of nodes and links among human and non-human components of the nitrogen cycle, representing the most recent (a), most cited (b), and random (c) sub-samples of the literature corpus. Network layout (relative position of nodes) was automatically optimized by *igraph* according to Fruchterman-Reingold method.

(Kolaczyk and Csárdi 2014), was ca. 0,79, so about 79% of all links in this network are reciprocated (bidirectional). The four realms of the nitrogen compartments are represented in the five nodes with the highest strength in the network (strength being the sum of all weights coming in, or out of a node; Table 1, SI-5. Together, these results illustrate the representation of links among all the different nitrogen compartments across different 'human' and 'non-human' realms, either through direct or indirect connections (see our conceptual figure, Figure 1).

Crop cultivation (CC) and Atmosphere (AT) play a central role in the network of the full corpus, as they are the nodes with the highest strength. These two nitrogen compartments were also strongly linked with each other. The link from Atmosphere to Crop Cultivation (AT → CC) was the strongest link in our network (weight = 21), while the nitrogen flow from Crop Cultivation to Atmosphere (CC → AT) was the fourth strongest link (weight = 18). The three nodes with the most outgoing links (out-degree) are CC, AT and Livestock and aquaculture (LA). CC has the maximum possible number of outgoing links in the network (14), since there are 14 nodes, and loops (a link from a node to itself) are possible. AT and LA are also the nodes with more incoming links (in-degree). On the other hand, Marine Sediment (MS) is the node that is least connected with the rest of the network. Comparing Figure 4 with the empirical representation of the nitrogen cycle of Gruber and Galloway (2008) (Figure 1 in their article), we found many similarities in the weighting of connections. This suggests that our network provides a reasonable overall representation of the nitrogen cycle. The clearest similarities are the land atmosphere nexus (AT ⇆ CC, AT ⇆ TB, & AT ⇆ SL, nodes here) and the separation of the MS node, burial in their figure. However, the 'human' nodes defined here and the cycling between them and other nodes are poorly represented in their Figure 1, despite being defined there. Our results for Crop Cultivation (CC) show the recognised magnitude of agriculture within the global nitrogen cycle (Gruber and Galloway 2008), and help explain the predominance of the 'human' realm that we noted earlier. Despite some relationship to Crop Cultivation (CC) and Atmosphere (AT), our findings do not fully align with estimates by Gruber and Galloway (2008), which pointed to nitrogen usage in food production, as well as nitrogen emitted to the atmosphere during fossil-fuel combustion, as the two main sources of anthropogenic nitrogen to the environment. In our N-Network, those anthropogenic flows of nitrogen are illustrated by the links from Industrial Nitrogen including chemical fertiliser to Crop Cultivation (IN → CC), and from Fossil Fuels & Energy to Atmosphere (FFE → AT), respectively, but were not the most prominent ones in our network; IN → CC had the fifth highest weight (17) of all links, whereas FFE → AT had only a weight of 7 (weights reflecting the number of reviewed studies identifying those links). This value belongs to the lowest quartile in our weight values' distribution. As a comparison, the four links with the highest weights in our network were from Atmosphere to Crop Cultivation (AT → CC;

weight = 21), from Atmosphere to Soil/Lithosphere (AT → SL; weight = 20), from Soil/Lithosphere to Atmosphere (SL → AT; weight = 20) and from Crop Cultivation to Atmosphere (CC → AT; weight = 18). This suggests that the interconnections between Atmosphere and Soil/Lithosphere, that are between 'non-human' realms, are more prominent than other linkages between 'human' and 'non-human' realms.

The three nitrogen sub-networks (most cited, most recent and random articles) show differences among themselves and in comparison to the nitrogen-network of the full corpus of articles (Figure 5a–c; see also Tables 2, 3 and 4, SI-5. All three sub-networks have lower values of graph density than the full network, which indicates an overall lower number of connections among nodes. The three sub-networks also show lower values of reciprocity than the full network, meaning that a lower percentage of links in those networks are reciprocated (bidirectional), with the 'random' network showing the closest reciprocity value (0,73) to the one of the full network. Similarly, compared to the full network, AT and CC are the nodes (Table 1) with highest strength values in the 'most cited' and 'random' networks, whereas in the 'most recent' network it is CC and TB. In the 'most cited' and 'random' networks, the four realms are represented in the five nodes with highest strength, as in the full N-Network. In the 'most recent' network, the four realms are represented after considering the six nodes with highest strength. In the 'most cited' network, MS remains as the node that is least connected to the rest of the network, as in the full network, with the difference that in the 'most cited' network it has no outgoing links whatsoever – in other words, there are no nitrogen flows from MS to other nodes. However, the 'most recent' and 'random' networks do not show the same pattern. In the 'most recent' network, HSE (humanity, society and economics) is the node (Table 1) that is less connected to the rest of the network, with no outgoing links (nitrogen flows) to other nodes. In the 'random' network this is FFE (fossil fuels and energy); nevertheless with one incoming and two outgoing links). Overall, these results show how using different samples of the literature could lead to different findings regarding the research questions at the core of our study. For example, considering any of the sub-networks would show a less interconnected nitrogen network than the one illustrated by the full network. Also, in the full network, only one of the three strongest nitrogen flows was between a 'human' and a 'non-human' realm (AT → CC), whereas in the 'most recent' network it was all three (TWB → CC, TWB → HCW, TB → IN), none of them being AT → CC as in the full network. The highest flow counts between human and nature nodes in the 'most recent' sub-network could be representative of recent increased awareness of human interconnection with N and associated disruption of the N cycle. These differences highlight the advantage of our sampling approach, combining the sub-samples of most cited, most recent and random articles (Scowen et al. 2021).

3.2. Content analysis

Sections 3.2.1 and 3.2.2 summarise the results of the content analysis and present a discussion of the findings in relation to key academic literature.

3.2.1. Exploring the nature of code interactions

The occurrence of the three search string relational terms – interconnec*, depend* and interdep* - across the corpus can be seen in Figure 1, SI-6. These relational terms appeared across 48 of the 84 papers (57%), with 'depend*' being the most common, appearing at least once in 47 papers. Very few papers showed co-occurrences of relational terms, i.e. 'interconn*' - 'depend*'' appear together in 4 papers, 'depend*' - 'interdep*' and 'interconn*' - 'interdep*' appear together in one paper each, and all three terms together in one paper (see SI-6 for overview of frequency and co-occurrence).

The generic relational term relat* was present in 16 papers and produced a set of quotes giving valuable comparative insights to those produced by the more specific relational terms included in the search string. Additional terms were also present in the corpus including: affect*, impact* and influenc*. Presence and co-occurrence of these additional terms was not calculated, but quotes were collected and reviewed to determine divergence or alignment with the insights emerging from the relational terms in the search string. Example quotes are presented in the following section.

From the three search string terms, four types of relational HNR codes were identified (Table 3),

Table 3. HNR code definitions and frequency across all papers ($n = 84$), materials can be coded across more than one code.

Human-Nature Relationships Node	#	Definition
Human-Human	33	Directed *interactions* between two (or more) 'human' elements of the system
Nature-Nature	35	Directed *interactions* between two (or more) 'natural' elements of the system
Human Depend on Nature[2]	14	Outcomes for humans controlled by, or *dependent* on, natural elements
Nature Depend on Human[1]	21	Outcomes for nature controlled by, or *dependent* on, human elements
Nature and Humans are related	30	*Relationships* between natural and human elements of a system without specific directionality and without explicitly described 'dependence'

defined by the nature of the quotes derived. One additional HNR code was identified from the generic relational term 'relat*'. Definitions of 'human' and 'non-human nature'/'natural' systems as used in the code titles and in the following sections can be found in Table 1, SI-3 and in the footnotes to Table 3.

Some studies document interactions between two (or more) 'human' elements of the system (node: 'human-human', $n = 33$), which relates to the prominent role of connections within the human realm found in the network analysis (Figure 3). These generally highlight that humans have disrupted the nitrogen cycle to enhance their own development. For example, our 'agrofood' systems are described as 'depending' on the 'control' of the nitrogen cycle, including management and artificial input. As one study states *'(. . .) half of humanity's food supply depends on Haber-Bosch N fixation. As a matter of fact, this process has put the global agrofood system on an industrial socio-ecological trajectory from which we now have great difficulty to escape'*. (Billen et al. 2021, p. 847) or, as mentioned by another study *'high input, high output, high surplus, and high dependence on synthetic fertilizer'* (Chen et al. 2016, p. 10). This also has consequences on humans' broader economic development which is, as these authors put it, *'to a certain extent dependent upon anthropogenic N creation'* (Zheng et al. 2002, p. 79) and on human health: *'It is important to recognize that the health impacts predicted to result from changing emissions and deposition and global climate change will occur in the context of changing population susceptibility and vulnerability'* (Peel et al. 2013, p. 129). Other authors highlight the spatial dimension of these human-human interactions, and notably the urban dependence on imported nitrogen: *'The massive dependence of the urban system on external N-containing products resulted in N pollution transfer from developed consumptive cities to production regions through trade'* (Dong and Xu 2020, p. 6).

A second type of node depicts interactions between two (or more) 'non-human nature/natural' elements of the system (node: 'nature-nature', $n = 35$). These relate to overall ecosystem features such as diversity, resilience and abundance, or trophic levels. Such interactions also relate to the (in)stability of nitrogen: *'resolving the question of how stabilisation of inorganic nitrogen affects the forest nitrogen cycle over the course of ecosystem development depends on whether stabilised nitrogen is eventually remineralized as inorganic nitrogen or as DON [dissolved organic nitrogen] . . ., and to what extent DON is in forms available for biotic uptake . . . or subject to loss from the ecosystem . . . '* (Perakis and Hedin 2001, p. 2257). Finally, other studies refer to higher-order, long temporal or large spatial scale effects: *'The biogeochemistry of nitrogen is almost entirely dependent on reduction-oxidation (redox) reactions primarily mediated by microorganisms (2), and to a lesser extent on long-term recycling through the geosphere'* (Canfield et al. 2010, p. 192).

Several studies explicitly describe a relationship of 'dependence': the dependence in a human-system on a natural element of the system (node: 'human depend on nature', $n = 14$), or vice-versa, the dependence of an outcome in a natural-system on a human element of the system (node: 'nature depend on human', $n = 21$). With respect to 'humans depend on nature', some authors articulate that the final outcomes of (food-)systems are ultimately controlled by, or 'dependent' on, natural elements. For example, natural systems display 'co-evolution' of their abilities to tolerate and respond to human actions and nature-based solutions can be implemented to solve human issues e.g. related to food systems; humans are mentioned as directly dependent on nitrogen, phosphorous and potassium within the system. One of quotes highlighted explores the intentional and explicit use of nature as part of: *'agro-ecological farming practices without dependency on synthetic N fertilizers (and pesticides)'* in order to *'feed Europe in 2050 with a healthy diet'* (Billen et al. 2021, p. 845). Other studies mention that humans depend on nature to regulate and reduce incidence of disease-causing organisms: *'(. . .) likely to cause varied and complex changes in the epidemiology of human diseases that depend on the life histories of disease-causing organisms and their vectors, the structure and composition of food webs controlling their abundance, and the overall sensitivity to N shown by the ecosystems in which they reside'*. (Townsend et al. 2003, p. 245). Human dependence on nature is highlighted by the transgression of planetary boundaries: *'We estimate that humanity has already transgressed three planetary boundaries: for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. Planetary boundaries are interdependent, because transgressing one may both shift the position of other boundaries or cause them to be transgressed. The social impacts of transgressing boundaries will be a function of the social – ecological resilience of the affected societies'* (Rockström et al. 2009, p. 1).

With respect to 'nature depends on humans', several studies depict the impacts of human action and a *dependence* of the state of the natural systems on these actions. For example, in stating that humans are responsible for the loss of biodiversity through excessive nitrogen application and impacts on specific organisms, e.g. mycorrhizal fungi/survivorship of only limited species, with knock-on, cascading, source-sink effects through the natural environment: *"The sensitivity of terrestrial ecosystems to N deposition of [anthropogenically derived reactive*

N] depends on rates of N deposition, as well as the sink strengths of plants, soils, and soil microorganisms for inorganic N". (Bowman et al. 2006, p. 1184). Other studies refer to the current dependence of cropland on chemical fertilisers, and on the need to develop new research approaches to promote another form of dependence on plant-microbe-soil nitrogen transformations for agricultural production instead: *'If there is societal interest in developing greater dependence on plant-microbe-soil N transformations for agricultural production (e.g. to reduce the fossil fuel used for production of N fertilizer by the Haber-Bosch process), then research approaches must better integrate plant physiology and soil microbial ecology'*. (Jackson et al. 2008, p. 353)

The last type of node illustrates *relationships* between 'natural' and 'human' elements of a system without specific directionality and without explicitly mentioning relationships of 'dependencies' ('Nature and humans are related' node, $n = 30$), dominated by the term 'relat*'. The associated quotes typically describe similar relationships as those mentioned-above but using more vague wording (e.g. 'related to') to refer to e.g. the impacts of human, in particular, agricultural activities on the nitrogen-cycle (e.g. '*human activities, mainly those related to crop-livestock production systems, have heavily disrupted the global Carbon and Nitrogen cycles, polluting local environments and increasing atmospheric concentrations of greenhouse gases ' (Harindintwali et al. 2021, p. 1)*, or the relationship of nitrogen with other global issues including urbanisation: *'more than half of the global top ten environmental issues (global warming, ozone depletion, biodiversity loss, acid rain, loss of forests, desertification, air pollution, water pollution, marine pollution and solid waste pollution) were related to the changes to nitrogen cycle in the 20th century [...] especially in urbanized regions'*. (Gu et al. 2012, p. 30).

Quotes from the additional search terms illustrate that other relational terms are present within the corpus of papers and that these terms indicate HNR in very similar ways to those previously described e.g. 'affect' - 'Human-induced changes in global nitrogen flows significantly affect the sustainability of food production' (Human-Human) (Liu et al. 2010, Pg. 8035); 'impact' - 'nitrogen from anthropogenic activities has interfered with the biogeochemical nitrogen cycle of natural ecosystems, resulting in ozone layer depletion, surface water eutrophication, soil acidification, nitrate pollution of water bodies' (Nature Depend on Human) (Huang et al. 2021, Pg. 50)"; and 'influence' - 'Nitrogen deposition and soil acidification can influence plant-pollinator interactions by affecting food quality; specifically, nectar and pollen' (Nature and humans are related) (Stevens et al. 2018, Pg. 1761)

3.2.2. Analysis

As noted in 3.2.1, the prevalence of 'Nature-Nature' and 'Human-Human' codes is an important insight from the network analysis: representing the regular articulation of reciprocal links within two (or more) 'natural' or 'human' elements of the system. The code 'Nature and Humans are related' ($n = 30$, where this link can be explicitly indicated by any relational term) is almost as prevalent, indicating a high level of articulated links between 'natural' and 'human' elements of the system. 'Nature Depends on Humans' ($n = 21$, where 'depend' has been explicitly used to describe the link) codes are notably less prevalent, but illustrate some occasions where outcomes for 'non-human nature' are explicitly described as being controlled by, or dependent on, 'human' elements. The 'Humans Depend on Nature' ($n = 14$) code is least prevalent, showing a lower presence within the corpus where outcomes for 'humans' are explicitly described as being controlled by, or dependent on, 'natural' elements. The imbalance between the last two codes suggest that direct human impacts upon nature are more regularly described within the corpus than the direct impact of nature on humans.

The presence and co-occurrence of a variety of relational terms suggest a level of nuance in the way in which the nitrogen cycle is described across the corpus. The dominance of 'depend*' as a relational term used in the corpus suggests that this is a relatively common way to describe the links between various realms of the nitrogen cycle. The definition accompanying Figure 1 ('the conditionality of any component of the biosphere needing interaction with other component(s) to sustain its existence') alludes to the strength and directionality of links that this suggests. The prevalence of 'depend*' can, therefore, be taken as an explicit recognition of, and/or desire by authors to convey some aspects of conditionality and reciprocity in their studies, especially those documenting elements that require interaction(s) with each other to sustain their existence (Figure 1 and SI-3).

It should be noted that even papers that use the most commonly found relational term ('depend*') do so to a limited extent, with 1–8 mentions per paper. There is some evidence of papers employing more than one search string relational term, but this is very limited aside from co-occurrence of the other terms with 'depend'. This suggests that relational language, while present, is still used to a limited extent to describe the context and findings of papers within the corpus. As noted in the introduction to this paper, the language we use in scientific spaces can carry important consequences for the way we see HNR. While more deeply exploring factors that might influence the use of relational terms was not a key focus of this study, it could be a feature of future work. It is possible that the lack of relational terms in the text of the corpus is shaped, to some extent, by the norms and conventions of scientific publishing. The empathetic or harmonising narratives created through relational language regarding HNR can be viewed as 'strong' or even 'emotive' (Besnier 1990). Discussions on the place of potentially emotive language in science and science communication (e.g. Taddicken and Reif 2020) highlight the risk that emotional language can harm the trustworthiness of scientists as well as the credibility of their arguments (König and Jucks 2019a, 2019b in Taddicken and Reif 2020), but conversely 'science that does not permit emotions seems culturally distant or even contradictory to the emotional(ised) daily lives that audiences experience' (Taddicken and Reif 2020).

3.3. Key findings and summary

This section presents key findings from sections 3.1 and 3.2 and summarises the overarching findings of the study.

There are some notable complementarities between the network analysis and the content analysis. In the content analysis we found that 'Human-Human' (n = 33) is one of the most prevalent codes, indicating a prevalence of interactions within 'human' components of the nitrogen cycle (rather than between 'human' and 'non-human nature' components). This was also seen in the network analysis, with a prominence of connections within the human realm. This acknowledges a recognition of the diversity and strong reciprocity of human activities influencing the nitrogen cycle (Vitousek at al, 1997). The code 'Nature and Humans are related' (n = 30) is almost as prevalent as 'Human-Human' in the content analysis, indicating a notable level of articulated links between 'natural' and 'human' elements of the system, which the N-network analysis also replicates though to a much lesser extent. Although the network analysis does not allow the explicit identification of dependence relationships, it does explicitly show the direction of the nitrogen flows between compartments, in this way complementing the content analysis and the aligning with the overall dominance of 'depend*' as a relational term.

One of the original motivations of this study was using quantitative and qualitative methods in compliment to explore the HNR nuances of the nitrogen cycle, in a manner endorsed by Kanter et al. (2020). We note that there is still a disciplinary imbalance in work on the nitrogen cycle, with much of the research corpus collected in our review being derived from natural and physical sciences – though there has been increasing involvement and representation of other disciplines since this disparity was noted by Norse (2005). Sutton et al. (2020) reflect that there is still a 'high degree of fragmentation between research on the different benefits and threats of reactive nitrogen and between the respective policy frameworks, especially at the global scale' (Sutton et al. 2020, p. 517). Many appreciate that: 'gaps and opportunities in nitrogen pollution policies still exist and require new interdisciplinary science to help to place the nitrogen management challenge in the context of the other environmental grand challenges of our time' (Melillo 2021, p. 759) and that while to some extent 'scientists have been successful in communicating the magnitude and the consequences (both positive and negative) of disruptions to the global nitrogen cycle' a more holistic approach is needed to address the 'Nr (reactive nitrogen) cascade' (Melillo 2021, p. 762). We believe that applying qualitative and quantitative (mixed) approaches to an existing corpus, as we have done in this manuscript, can go some distance towards collating insights from different research methodologies and norms of data presentation to yield new interpretations (Ashley and Boyd 2006; Diloreto and Gaines 2016). Mixed approaches allow us to bring diverse observations in to concert without drawing inappropriate equivalences.

Norse (2005) states that this prior lack of involvement of other disciplines has particularly reduced our ability to fully grapple with the 'spatial or temporal importance' of risks to human and ecosystem health from human alteration of the nitrogen cycle, and that these insights can have direct implications for those conducting further research and with roles in making and supporting policy on the topic. Cross-scale interactions play a crucial role in understanding and shaping all complex systems, where changes at one scale can propagate and generate significant cascading non-linear impacts (Hessen et al. 1997; Levin 1998; Erisman et al. 2013; Preiser et al. 2018) and detailed diagnoses can help to highlight un- or underexplored elements within systems of interest. The process of collating and identifying insights from the corpus into nodes and codes in our network and content analysis has provided an additional granularity to the individual papers in the corpus and helps explore and visualise a diversity of interactions taking place across human and non-human components of the nitrogen cycle. It can be likened to viewing an intricate mural from afar versus up close; the general impression differs significantly from the detailed textures and nuances that can be observed at close range. Our methodological approach presents an opportunity to transcribe and explore the diversity implicit within a corpus of existing literature, understand how and where these various components are situated in relation to one another, and begin to explore how these might interact across different (spatial and temporal) scales.

It is, therefore, our hope that our mixed-method approach, which has practical value in conducting literature reviews, can also play a reflective and supportive role in the framing of future research, responding to the encouraging statement that: 'curiosity, common sense, scientific advancement and societal concern will continue to drive future advances in the interaction between humans and the nitrogen cycle as we try to reap nitrogen's benefits, while minimizing its negative impacts on people and ecosystems' (Galloway et al. 2013, p. 1).

4. Limitations of the study and further work

There are several limitations to this study which the authors would like to acknowledge. The conceptual framing of 'humans' and 'non-human nature' in our own analysis does reflect a duality but only as an attempt to verify how far this is reflected in the literature. We recognise the risk of this within our work, therefore future work could try to look for evidence of publications that do not make this separation.

Further research could cover a bigger sample of literature, testing when a saturation point would be achieved, beyond which the main findings would not change in a significant way. The sample sizes of reviewed articles for the sub-networks are smaller than the ones for the full network, which might introduce some statistical bias and should be considered when doing direct comparisons between the sub-networks and the full network. We only reviewed literature in English. We acknowledge that while English is a dominant working language for academic publication, continuing to conduct review studies in English potentially perpetuates an English language bias and limits representations of the global context.

In the network analysis, we defined the weighted links between nodes by accounting for how many articles established quantitative, empirical linkages between the different nitrogen compartments. This did not automatically allow us to distinguish between different types of linkages between nitrogen compartments (e.g. dependencies). It highlights the importance of complementing the analysis of empirical linkages with the qualitative textual analysis we conducted. Further research could attempt to more fully integrate both approaches, by categorizing the links in the network according to different types. Nevertheless, based on our experience, to do this for each linkage identified in each article often implies dealing with a high degree of subjectivity making the task quite challenging. This type of integrated analysis of social and ecological nodes remains challenging because of the different conceptualizations of nodes and links in the social and ecological realm (Bodin et al. 2019) and differing terminology (Sayles et al. 2019). To build on both analyses it would also be possible to further detail the ways in which quantitative data and qualitative data provide complimentary or divergent pictures of the relationship between different components of the nitrogen network, not only across but also within individual papers.

In our content analysis we focussed on a limited number of terms which had been iteratively derived in the creation of the search string. Future work might consider the deeper exploration of additional relational terms. It might also seek to map the co-occurrence of these relational terms more comprehensively across different papers and to map these back to the quantitative findings from the same paper.

As noted within the planetary boundaries literature (Rockström et al. 2009, 2023; Steffen et al., 2015; O'Neill et al. 2018) we know that all of Earth's systems are interlinked and require careful management, in the face of an ever-increasing human intervention in the Earth system. For further research, our approach could be extended to cover other important biogeochemical cycles, like carbon. This would provide a more integrated illustration of HNR (as depicted in the literature) in relation to global biogeochemical cycles. Alternatively, at the ecosystem scale, work on nitrogen (or other macro nutrient) tracing in systems with clearly defined boundaries should provide definitive examples of dependence pathways. Both ideas represent promising avenues for further research.

5. Conclusion

Setting out to explore the relationship between 'humans' and 'non-human nature' represented in published scientific literature on the nitrogen cycle, we used a literature review and two analytic methods to explore the corpus.

We believe that our work and findings here attest to the utility of combined network analysis (quantitative) and content analysis (qualitative) to summarise links across the nitrogen cycle in peer-reviewed academic literature. These links have been identified, illustrated and analysed to achieve the research aims. The network analysis represents nitrogen flows, as identified and quantified in the literature corpus. In that sense, it gives an idea of which components (human and non-human) of the nitrogen cycle are more or less connected (directly and indirectly) in the scientific literature, as well as the directionality of those flows. The content analysis then looks at how the connections between nitrogen compartments are qualified, giving more information on the type of connections defined in literature. This shows the complementarity of the network analysis and the content analysis, and the added value of our approach, bringing the two together.

There is a growing weight of academic and practitioner discourse arguing that considering 'humanity' and 'nature' as separate is the origin of many environmental problems, and an increasing unrest with the fact that this view does not appropriately describe humanity's place on the planet. If we do not recognise this explicitly, in the ways that we conceptualise and communicate the structure and function of global systems like the nitrogen cycle, there is little hope of achieving the transformative changes to environment and society that we need to tackle global ecological change and the escalating climate crisis. We believe that a deeper understanding of the representation of HNR and the nitrogen cycle in academic papers has utility for science communication and work at the science-policy interface. We hope that this work can play a useful role in highlighting and reformulating narratives around the nitrogen cycle to better consider the varied and diverse role that human actions play.

Notes

1. a flexible definition of *nature* that 'minimizes the degree of human control over the dynamic and evolutionary potential of nonhuman species and ecosystems' (Ridder 2007) (in Clayton et al. 2017)
2. We note here that it is important to differentiate between the state of a natural system depending on human N or system itself depending on human N. We also note that the language here ('depend on') is that of the authors in the corpus rather than the authors of this paper and in all cases is used as a shorthand for the fuller definition of 'controlled by, or *dependent* on'

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