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Research trends of nature-based solutions: from urban to climate change

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As one of the efforts to combat climate change and the biodiversity crisis, an interest in nature-based solutions (NbS) has been growing. Although there have been diverse discussions on NbS, it is still insufficient to find a quantitative evaluation of the global research trends in which field and to what extent NbS has been studied. In this regard, this study employed latent Dirichlet allocation (LDA) topic modeling and keyword analysis to quantitatively evaluate the research trends of NbS. Among research papers on NbS searched on SCOPUS, 2,625 studies (2009–2022) were analyzed by LDA. As a result, NbS-related articles were classified into seven topics (i.e., Urban governance, Urban green infrastructure, Wastewater treatment, Coastal protection, Flood mitigation, Carbon sequestration, and Sustainable agriculture). Of these, the urban and water-related topics accounted for the largest proportion. In contrast, the carbon sequestration and sustainable agriculture topics accounted for a smaller proportion, but the proportion significantly increased over time. As a result of keyword analysis, the frequency of urban and water keywords remained high. In contrast, the frequency of climate change and carbon keywords was low and has recently increased. In the keyword network, the co-occurrence frequency and connection of urban and water keywords were initially high. Still, over time, keywords related to climate change and carbon increased similarly to those related to urban and water. The findings of this study imply that NbS has mainly focused on urban and water-related researches. Still, climate change and carbon-related researches may also be actively handled in relation to NbS in the near future.

KEYWORDS

nature-based solution, research trend analysis, topic modeling, keyword analysis, climate change

1 Introduction

Among diverse efforts to combat the climate change and biodiversity crises faced by human beings, attempts to find solutions based on nature have attracted huge attention (Pettorelli et al., 2021). Such attempts are not a new concept and have existed, which can be found in various regions where residents have used nature to solve problems (e.g., Berkes et al., 2000; Albuquerque et al., 2021). However, since the term “nature-based solutions

(NbS)” was first coined in World Bank report in 2008 (MacKinnon et al., 2008), there have been more studies using this term, and recently, it has evolved into a political agenda in international communities (Seddon et al., 2020, 2021). For instance, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] (2019) has introduced NbS as a cost-effective measure to achieve sustainable development goals (SDGs), which are essential for global sustainability. The Intergovernmental Panel on Climate Change [IPCC] (2022) has also accepted with very high confidence that NbS can provide human beings with benefits for climate change mitigation and adaptation, and contribute to achieving other SDGs.

The NbS definition has not yet been agreed upon. Still, the definitions suggested by the International Union for Conservation of Nature [IUCN] (2023) and the European Commission [EC] (2023) are the most frequently utilized. IUCN defined NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits (Cohen-Shacham et al., 2016).” On the other hand, EC defined NbS as “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring diverse nature and natural features and processes into cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions. Nature-based solutions must benefit bio-diversity and support the delivery of ecosystem services (European Commission [EC], 2023).” Such definitions clarified by the two organizations have common features in that they are a method (1) through nature, (2) while solving social issues, and (3) benefiting biodiversity, but they also have different features in how they involve nature. IUCN emphasizes solutions to protect, manage, and restore nature, whereas the EU is aware of a wider range of solutions, encompassing solutions inspired by or supporting nature. The definition by IUCN is more general, while EC’s is more specific regarding scope or applicability (Bianciardi et al., 2023).

Despite the ongoing debate on the definition, the research area of NbS, which attempts to solve social issues based on nature, has already been widely recognized. For example, Pettorelli et al. (2021) indicated that NbS has handled fields that address several interconnected social challenges, such as climate change, water security, human health, disaster risk reduction, and food security. Seddon et al. (2021) recognize a wider range of fields as the scope of NbS: greenhouse gases (GHGs) reduction, flood and erosion control, coastal defense, cooling and shading, food and water security, livelihoods, cultural values, and social capital. International Union for Conservation of Nature [IUCN] (2023) classified NbS topics into agriculture and soil biodiversity, disaster risk reduction, ecosystem restoration, nature-based solutions for climate, and nature-based solutions for cities. In other words, NbS has a broad concept that encompasses a wide range of environmental, social, and economic challenges. As the NbS concept became so widely known, some countries such as Germany have recently adopted the concept and established the national policy framework (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection [BMUV], 2023). IUNC has also

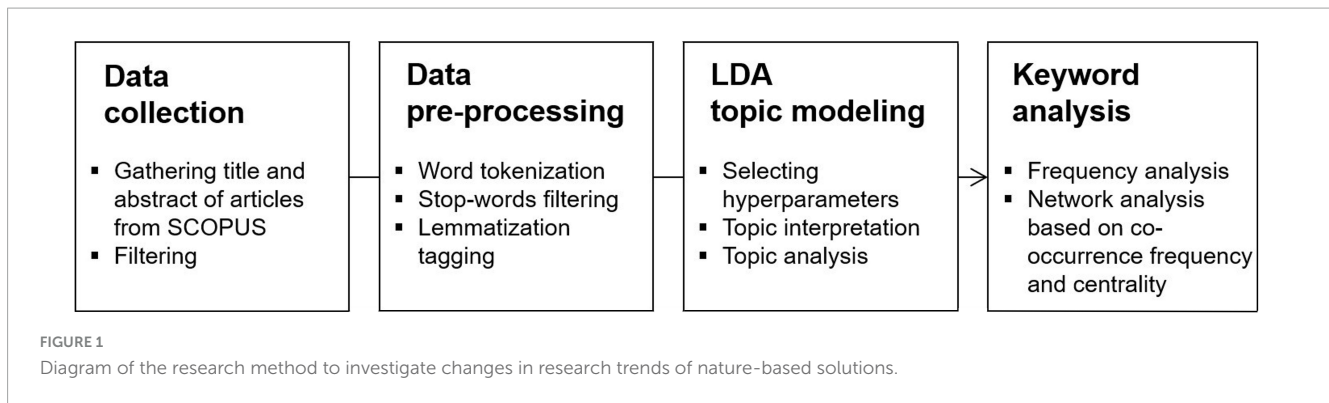
developed a global standard for NbS to help design, assess, strengthen, and upscale NbS interventions (Le Gouvello et al., 2023).

Under the circumstances where the application range of NbS is wide, it is necessary to specifically understand which fields should be considered NbS, and what kinds of related research are ongoing. However, finding studies covering comprehensive NbS research trends with quantitative approaches is still insufficient. Although there have been several attempts, they have their own significance and limitations. For instance, Su et al. (2023) targeted 176 NbS articles focusing on urban wastewater management, analyzed the research trends in a bibliometric method, and classified research fields into four groups (i.e., green infrastructure, stormwater runoff, climate change mitigation and adaptation, and flood risk and biodiversity), but failed covering the entire fields of NbS. Nyika and Dinka (2022) targeted 137 articles covering NbS cases in Africa, and classified them into six areas (i.e., integrated environmental management, water security, health, climate change mitigation and adaptation, food security enhancement, and disaster risk reduction) for analysis, but faced limitations in that they only provided region-specific information rather than global trends. On the other hand, Parker et al. (2020) quantitatively reviewed 54 articles with both NbS and climate change in the title, but the number of research papers analyzed is minimal, and representativeness should be more secure; to this end, a time-efficient and quantitative approach is required to analyze a large number of research papers. As part of this attempt, Castellanos et al. (2020) attempted to analyze the research trends of NbS applied to urban areas in Europe via a text mining technique. However, they could not cover the entire field; they only focused on three review reports. Recently, Choi et al. (2023) tried to analyze the research trend on the entire field of NbS using dynamic topic modeling; however, it focused on only topic level not on keyword level. Consequently, there is a need for an efficient and quantitative analysis of the comprehensive research trends of NbS, which is rapidly growing worldwide.

Under the circumstances, this study aims to answer the question: “How have the global research trends in NbS changed?” To answer this question, this study utilized latent Dirichlet allocation (LDA) topic modeling analysis and keyword analysis that help researchers quantitatively analyze research trends. Additionally, it targeted NbS-related articles published from 2009, after 2008, when NbS was first officially utilized, to 2022, and analyzed NbS research trends. By identifying changes in NbS research trends, this study attempted to provide meaningful insights into what kinds of research have received attention and what sorts of research are likely to be handled more in the near future. The findings of this study will provide scientists, policymakers, and the general public unfamiliar with the NbS concept, with a comprehensive picture to help them easily understand NbS.

2 Materials and methods

Figure 1 is an overall diagram of the research method, consisting of data collection, data pre-processing, LDA topic modeling, and keyword analysis.

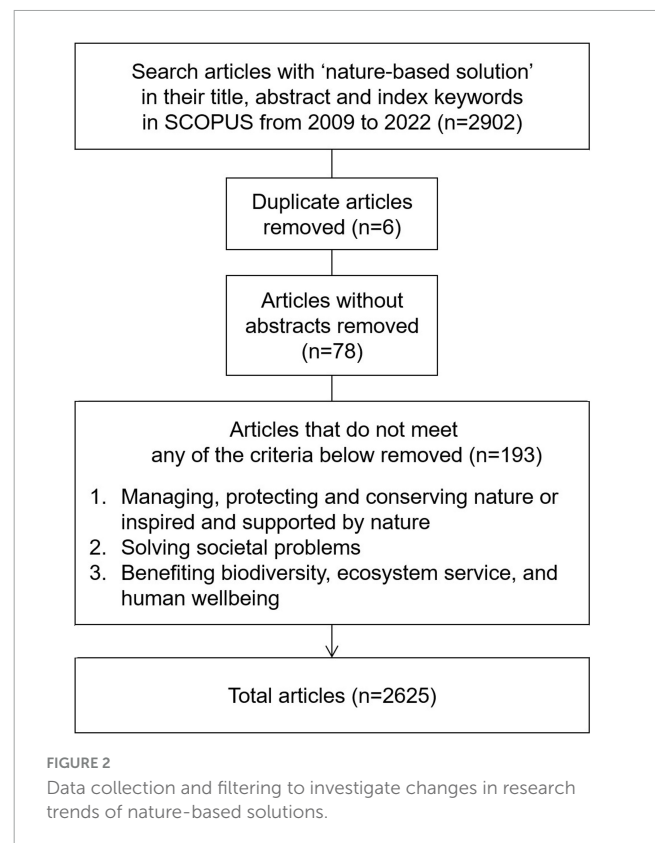


2.1 Data collection

Figure 2 shows the data collection and filtering phase. This study set the research period from 2009, after 2008, when the NbS term was first formulated, to 2022. The titles and abstracts of 2,902 articles in English were collected from SCOPUS, an academic journal search website, for which “nature-based solution” was found in the title, abstract, and index keywords. The analysis excluded six duplicates and 78 articles for which no abstract was provided. On the one hand, since “nature-based solutions” is a compound term, words such as “nature,” “based,” and “solution” were used separately, but articles unrelated to NbS were also included. On the other hand, there were several research papers belonging to NbS, even though only “nature-based” was used, and the following other terms other than “solution” (e.g., climate solution, cooling, infrastructure, management, health solution, and social welfare) were utilized during the search. Thus, two researchers independently reviewed the research papers. They included several articles in the analysis if they contained the compound term “nature-based solution” in the title, abstract, or index keywords. After reading the abstracts of the remaining papers, they filtered and excluded papers unrelated to NbS. The filtering criteria were based on the NBS definitions suggested by IUCN and EC definitions: (1) Does the method use nature, (2) Can it solve social issues? And does it bring (3) benefits to biodiversity, ecosystem services, and human welfare/wellbeing? The 193 research papers that do not meet any of these criteria were excluded. As a result, a total of 2,625 articles were utilized for analysis.

2.2 Data pre-processing

To pre-process the collected data, tokenization was performed via Python, which divides text data into tokens, the smallest unit of meaning. Since all tokenized words are not meaningful, stopwords in English, special symbols, and punctuation marks provided by the Natural Language Toolkit of Python (3.11.4 ver.) were removed. Each token was tagged with a part of speech, such as a noun, adjective, verb, or adverb, and then lemmatization tagging was performed to extract only nouns and adjectives. Nouns and adjectives frequently utilized in all articles were eliminated (Supplementary Table 1). Additionally, words with less than two



syllables were removed, lowercase conversion was performed on all words, and singular and plural words were treated equally.

2.3 Latent Dirichlet allocation topic modeling

Topic modeling is a text mining technique that helps find hidden semantics in a set of documents and classify them into topics; LDA is the most frequently utilized tool among the various topic modeling tools. This method recognizes text data as three structures – documents, words, and topics. It assigns each document and word to a specific topic based on Dirichlet prior distribution. A detailed theoretical description of LDA can be found in Kherwa and Bansal (2019) or Vayansky and Kumar (2020).

Hyperparameters were adjusted to select the optimal number of topics at the topic modeling phase. The number of topics is the crucial hyperparameter in LDA. If an insufficient number of topics is selected, the content of a topic is too broad, while if too many topics are selected, small and similar topics are created. There are numerous ways to determine the number of topics in topic modeling (Kherwa and Bansal, 2019), but this study selected the number of topics based on the coherence score, which is a frequently used criterion (Chang et al., 2009; Greene and Cross, 2017; Yao and Wang, 2020). The coherence score is an indicator of measuring the consistency of the keywords that comprise a topic; a higher coherence score indicates the keywords better describe the topic (Röder et al., 2015). To determine the number of topics for LDA, modeling was conducted several times with different combinations of passes and iterations, and seven topics with the highest coherence score of 0.050 (passes = 50, iteration = 320; Figure 3) were selected.

This study targeted all data collected from 2009 to 2022 and performed an LDA topic modeling analysis through Python's "Gensim" library. Although the model assigns each article to a topic, the content must be interpreted by researchers. Considering that two researchers interpreted the topics based on the top 20 keywords with the highest probability of being assigned to each topic and 10 representative articles (Supplementary Table 2). The interpretation of the topics was reviewed and revised by all co-authors. Next, a linear regression analysis with the Python "statsmodel" library was performed to test the significance of trends over time in the number of articles of each topic (i.e., topic frequency) and the proportion of articles in each topic among the total number of articles (i.e., topic proportion). The independent variable was set as the year of publication, and the dependent variables were set as topic frequency and proportion. The significance level was set at 95%. If the regression coefficient is positive, the topic is a hot topic (i.e., significantly increased by time). If it is negative, it is a cold topic (i.e., significantly decreased by time).

2.4 Keyword analysis

Simple frequency analysis of keywords analyzes how frequently a keyword is used in articles published during a certain period. To identify changes in the frequency of keywords comprising NbS research, this study divided the period since 2017, when the number of articles was assumed to be sufficient because more than 70 research papers were annually published, into three periods of 2 years each (i.e., 2017–2018, 2019–2020, and 2021–2022), and compared the changes per period. During this period (2017–2022), more than 97% of all research papers were published.

Keyword network analysis is a methodology that extracts meaningful keywords from a text and creates a network by figuring out connections between keywords playing a core role (Lee, 2014). Through network analysis, relationships between keywords are expressed with nodes and links. In this study, the size of nodes was set as the centrality value of keywords, and the thickness of links was set as the co-occurrence frequency of keyword pairs. Here, centrality refers to "the degree to which a particular node is centrally located with intensive connections." This study employed

two types of centralities (i.e., degree centrality and betweenness centrality); degree centrality has a higher value when the number of links that are linked to a particular node increases, and betweenness centrality has a higher value when a particular node links with the shortest distance (i.e., fewer links) between two other nodes (Yu and Lee, 2008; Yan and Ding, 2009). For each period, the top 20 keywords were selected as nodes in order of higher centrality values. The link connecting the corresponding pair was expressed in bold when the higher co-occurrence frequency of a specific keyword pair appears, since the higher co-occurrence frequency means the higher connection between keywords simultaneously found in a document (Cambrosio et al., 1993; Ding et al., 2001). After the keyword network analysis using the "networkx" library in Python, the changes in the keyword network were compared between the three periods.

3 Results

3.1 Latent Dirichlet allocation topic modeling

3.1.1 Overall papers

Figure 4 indicates the number of NbS-related articles searched on SCOPUS from 2009 to 2022. From 2009 to 2016, only 1–36 articles (less than 3% of all research papers) were annually published, but from 2017, more than 70 research papers were annually published. The number rapidly increased, reaching 1,008 research papers published (38% of the research papers) in 2022.

3.1.2 Topic interpretation

Based on the LDA topic modeling results, NbS research was classified into seven topics (Table 1). The keywords were presented in descending order in Table 1 in the order of the highest probability of being assigned to each topic. In other words, the higher the ranking, the more important the keyword in the corresponding topic was. The name and interpretation of the topic were determined based on the top 20 keywords and 10 representative research papers.

The topics can be interpreted as follows. Topic 1 is "Urban governance." The articles on this topic handle people's perception and participation surveys, governance, policies, conceptual frameworks, and societal paradigms needed to solve diverse urban issues (e.g., climate change, water scarcity, and wastewater treatment) through NbS. Here, NbS is recognized as a catalyst for urban regeneration strategies that promote climate resilience via nature, improve the wellbeing and health of citizens, and restore neighborhood belonging (e.g., Mahmoud et al., 2021; Hardoy et al., 2022; Wamsler et al., 2023). There is less focus on specific technologies or engineering applications for implementing NbS but more on conceptual frameworks, values and norms, and policy directions for transitioning and evaluating systems (e.g., Beceiro et al., 2020; Gunn et al., 2021).

Topic 2 is "Urban green infrastructure." The articles on this topic focus on nature-based infrastructure that can contribute to handling urban microclimate-related issues. For example, to mitigate heat islands, where temperatures in cities are significantly higher than those in surrounding areas, green

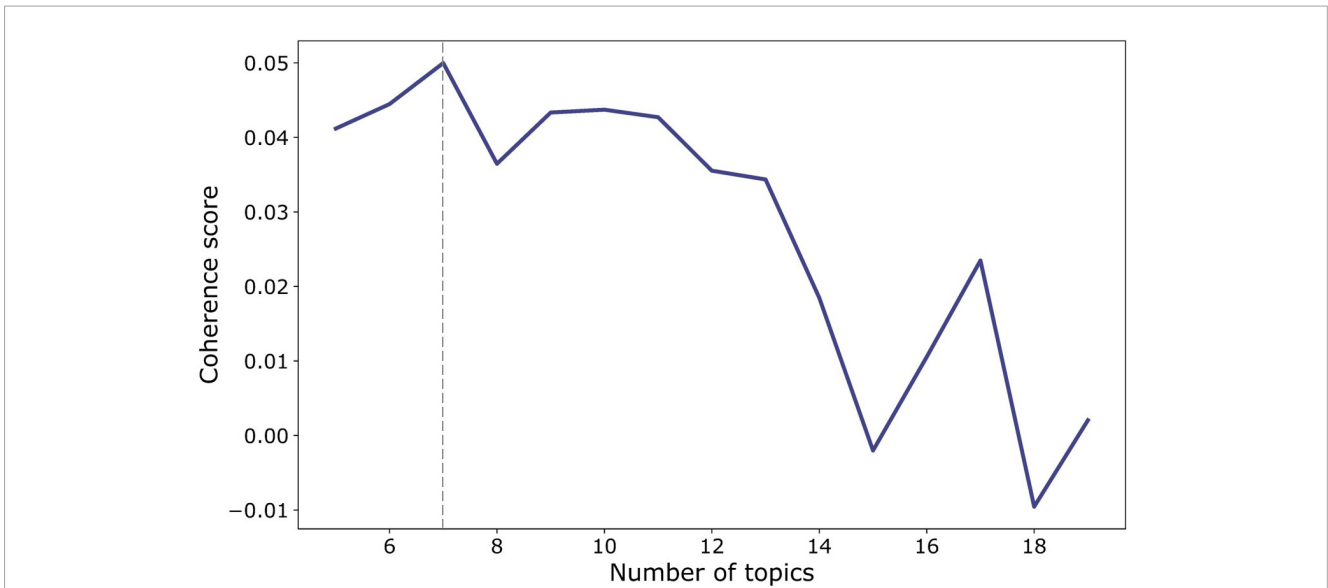


FIGURE 3 Coherence score of latent Dirichlet allocation (LDA) topic modeling depends on the number of topics. The highest coherence score was observed for seven topics.

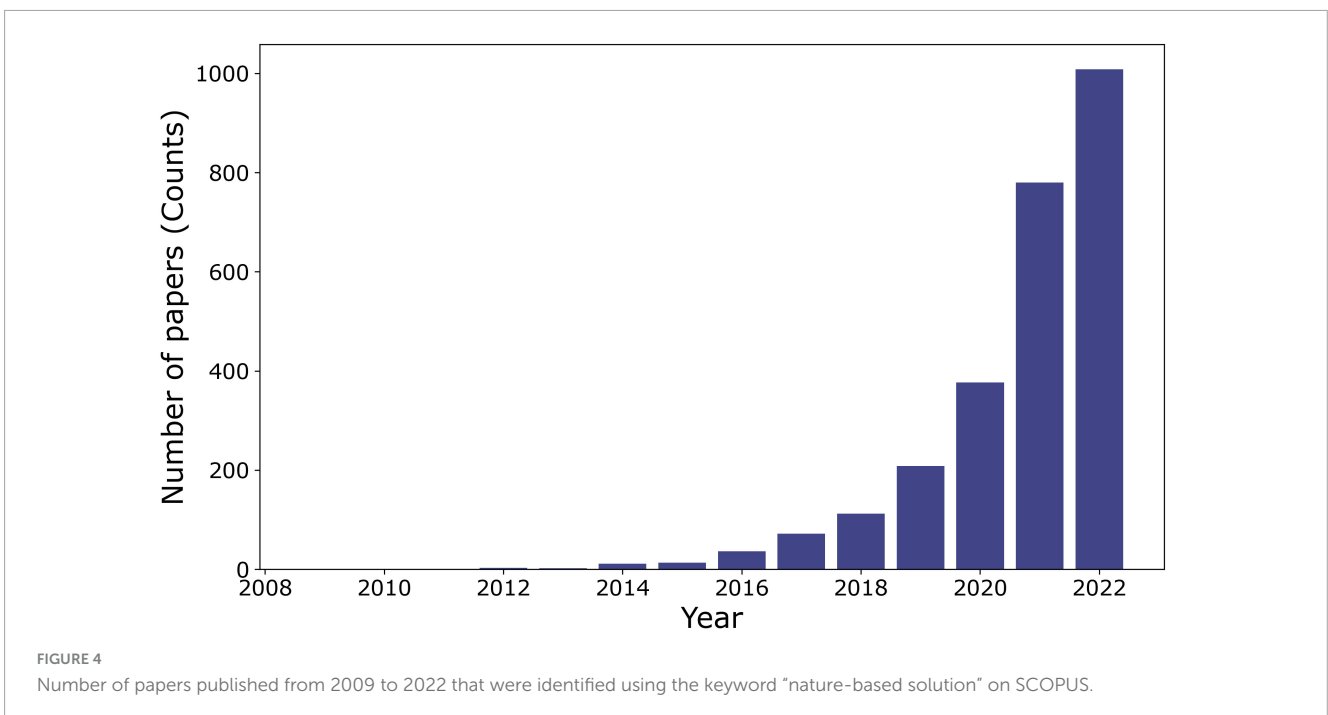


FIGURE 4 Number of papers published from 2009 to 2022 that were identified using the keyword “nature-based solution” on SCOPUS.

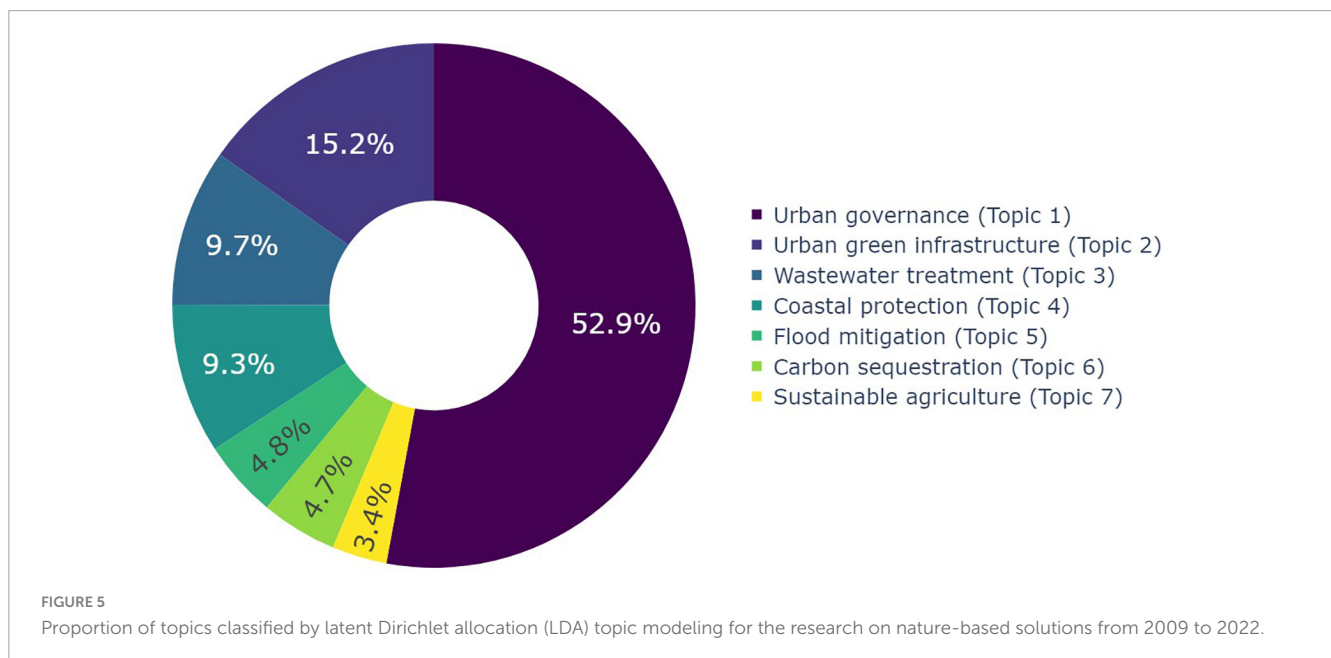
infrastructure utilizing plants or blue infrastructure utilizing water (e.g., rooftop gardens, open green spaces, and waterfront parks) have been suggested as nature-based solutions. There have been empirical studies to primarily demonstrate the heat island mitigation effectiveness through spatial mapping of these green-blue infrastructures, analysis of their relationship with land surface temperature, and model scenarios (e.g., [Nastran et al., 2019](#); [Alves et al., 2022](#); [Du et al., 2022](#)). Other examples encompass research on the role of urban street trees or land cover in regulating urban surface runoff (e.g., [Zabret and Šraj, 2019](#); [Xu et al., 2020](#)). In contrast to Topic 1, Topic 2 primarily focuses on quantitative

validation of the problem-solving effectiveness of physical urban infrastructures based on plants or water.

Topic 3 is “Wastewater treatment.” The articles on this topic cover wastewater or greywater purification methods using specific plant species, biofilters of plants or microorganisms, or constructed wetlands. These contaminated waters have pollutants such as heavy metals and feces and excessive amounts of nutrients, such as phosphorus and nitrogen. The articles on this topic primarily focused on filtering such pollutants based on nature (e.g., [Barron et al., 2020](#); [Arslan and El-Din, 2021](#); [Montenegro et al., 2021](#); [Cavazzoli et al., 2022](#)).

TABLE 1 The top 20 keywords of topics classified by latent Dirichlet allocation (LDA) topic modeling for the research on nature-based solutions from 2009 to 2022.

Rank	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6	Topic 7
	Urban governance	Urban green infrastructure	Wastewater treatment	Coastal protection	Flood mitigation	Carbon sequestration	Sustainable agriculture
1	Urban	Urban	Water	Coastal	Flood	Carbon	Biodiversity
2	Climate	Area	Soil	Vegetation	Water	Climate	Soil
3	Ecosystem	Green	Treatment	Erosion	Risk	Emission	Restoration
4	Change	City	Plant	Protection	River	Energy	Species
5	Benefit	Forest	Wastewater	Sediment	Management	Forest	Food
6	Environmental	Change	Removal	Restoration	Land	Change	Change
7	Policy	Tree	Wetland	Wave	Measure	Sequestration	Ecosystem
8	Management	Spatial	Nutrient	Model	Area	Global	Agricultural
9	Social	Climate	Pollutant	Wetland	Tourism	Mitigation	Agriculture
10	City	Land	Technology	Natural	Event	Gas	Climate
11	Service	Scenario	Organic	Area	Catchment	Rate	Conservation
12	Development	Service	Concentration	Sea	Mitigation	Land	Crop
13	Green	Infrastructure	Performance	Habitat	Reduction	Greenhouse	Production
14	Sustainable	Space	Nitrogen	Level	Change	Blue	Forest
15	Challenge	Model	Efficiency	Marsh	Basin	Stock	Plant
16	Project	Vegetation	Metal	Mangrove	Hazard	Cost	Diversity
17	Infrastructure	Ecosystem	Rate	Ecosystem	Model	Reduction	Land
18	Framework	Heat	Quality	Engineering	Natural	Ecosystem	Loss
19	Adaptation	Use	Condition	Condition	Hydrological	Market	Ecological
20	Implementation	Landscape	Material	Seagrass	Flow	Sink	Habitat



Topic 4 is “Coastal protection.” The articles belonging to this topic chiefly handle nature-based solutions to mitigate erosion or impacts from waves on seashores. As a representative example, such articles focus on how effectively waves can be mitigated through such methods as seagrass meadows, salt marshes, mangrove

forests, oyster breakwater reefs, and sand trapping fences for coastal dunes while aiming to protect the coast from erosion (e.g., Chowdhury et al., 2019; Eichmanns and Schüttrumpf, 2020; James et al., 2020; van Veelen et al., 2021; Zhao and Nepf, 2021; Zhu et al., 2022).

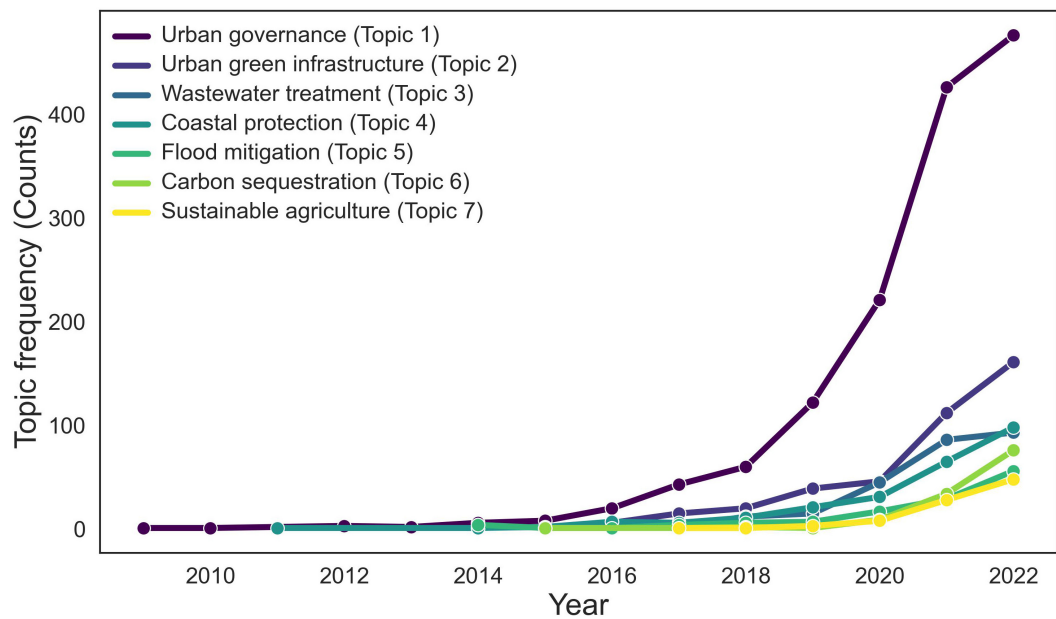


FIGURE 6

Number of papers of each topic (i.e., topic frequency) classified by latent Dirichlet allocation (LDA) topic modeling from 2009 to 2022.

Topic 5 is “Flood mitigation.” Articles on this topic address nature-based solutions to prevent or mitigate floods, which have become more frequent in recent years due to climate change, urbanization, and land use change. Representative solutions suggested encompass various types of wetlands, detention ponds, flood-peak polders, and tree planting that can store and slow down flash flood waters and be cost-effective measures to buffer flood damage and improve the resilience of nature, compared to engineering solutions (e.g., Bokhove et al., 2019; Wu et al., 2020, 2022; Tseng et al., 2022; Ungvári and Kis, 2022).

Topic 6 is “Carbon sequestration.” Articles on this topic deal with nature-based solutions for mitigating carbon dioxide (CO₂), the primary GHGs causing climate change. Forest restoration or reforestation has been suggested as the most effective means to capture and store CO₂ in the air; while targeting primary forest, secondary forest, and urban forest, there have been studies with a more focus on monitoring and predicting changes in carbon storage based on the current carbon storage, and the deforestation and reforestation (e.g., Reynolds et al., 2017; Fuller and Dwivedi, 2021; Elias et al., 2022; Matthews et al., 2022). Additionally, the following measures have been discussed as important nature-based solutions to sequester and store carbon: restoring peatlands, which have accumulations of peat created by the partial decomposition of plant organic matter under waterlogged conditions, or creating seagrass in the ocean (e.g., Gallagher et al., 2022; Strack et al., 2022).

Topic 7 is “Sustainable agriculture.” Research papers focus on various solutions contributing to building agricultural resilience, improving soil health, and coexisting with biodiversity. In other words, they explore methods to help food security without compromising biodiversity. For example, several studies developed how to increase genetic diversity by crossing crops with their wild relatives (e.g., Satori et al., 2021; Subbarao et al., 2021), and other studies developed land management methods such as organic amendments, crop rotation, and the creation of pollinator-friendly

landscapes to further increase natural pollination by insects and reduce pests (e.g., Karuri, 2022; Perrot et al., 2022). Such methods can eventually reduce chemical inputs to agriculture and help maintain production while conserving biodiversity (e.g., Catarino et al., 2019; Valkó et al., 2022).

3.1.3 Topic proportion

Figure 5 summarizes the proportions of articles on each topic among all research papers. Topic 1 (Urban governance) and Topic 2 (Urban green infrastructure) are related to urban themes, dominating the majority of NbS research as 68.1% of the total. Topic 3 (Wastewater treatment), Topic 4 (Coastal protection), and Topic 5 (Flood mitigation), which are related to water, account for 23.8% of the total. Topic 6 (Carbon sequestration) and Topic 7 (Sustainable agriculture) are relatively smaller than other topics in the entire NbS research.

3.1.4 Temporal change of topics

Figure 6 shows the trend of each topic’s number of articles (i.e., topic frequency) over time. All topics significantly increased over time (all $p < 0.05$; Table 2) while showing different patterns with each other. First, Topic 1 (Urban governance), accounting for more than half of the total, rapidly increased at an overwhelmingly large rate compared to other topics since 2016. Topic 2 (Urban green infrastructure) also showed a relatively large increase during the same period. Topic 3 (Wastewater treatment) and Topic 4 (Coastal protection) presented similar growth rates, although their rankings changed several times. The increase rate of Topic 5 (Flooding mitigation) took the ranking after Topic 3 and Topic 4 until 2020, but since 2021, the ranking was overtaken by the growth rate of Topic 6 (Carbon sequestration). The increase rate of Topic 6 was greater than water-related topics such as Topic 3, 4, and 5 since 2021. Finally, Topic 7 (Sustainable agriculture) continuously showed the smallest increase rate over the observation period.

TABLE 2 Regression coefficients and p -values of topic frequency and topic proportion classified by latent Dirichlet allocation (LDA) topic modeling from 2017 to 2022.

Topic	Frequency			Proportion		
	Coefficient	p -value	Hot/cold	Coefficient	p -value	Hot/cold
Topic 1	96.057	0.002	Hot	-0.017	0.141	Normal
Topic 2	28.943	0.007	Hot	-0.012	0.116	Normal
Topic 3	20.200	0.003	Hot	0.011	0.210	Normal
Topic 4	18.057	0.005	Hot	0.000	0.945	Normal
Topic 5	9.686	0.013	Hot	-0.001	0.692	Normal
Topic 6	13.686	0.031	Hot	0.012	0.038	Hot
Topic 7	9.171	0.016	Hot	0.007	0.011	Hot

Figure 7 indicates the temporal trend of the proportion of articles of each topic (i.e., topic proportion) among all research papers. As for the analysis of the temporal trend since 2017, when all topics began to appear simultaneously to 2022, the proportions of Topic 1 (Urban governance) and Topic 2 (Urban green infrastructure) decreased (60%→47% and 21%→16%, respectively) but this was not statistically significant. Topic 3 (Wastewater treatment), Topic 4 (Coastal protection), and Topic 5 (Flooding mitigation) showed temporal variations but did not indicate statistically significant fluctuations. On the other hand, the proportions of Topic 6 (Carbon sequestration) and Topic 7 (Sustainable agriculture) increased significantly (1%→8% and 1%→5%, respectively, and both of them are $p < 0.05$; Table 2).

3.2 Keyword analysis

3.2.1 Keyword frequency

In general, the frequency of all keywords significantly increased from the first period (2017–2018), the second period (2019–2020), and the third period (2021–2022), reflecting the steady increase in research papers on NbS (Table 3).

When comparing the ranking of keywords per period, urban showed the highest frequency among all keywords during those periods and continuously ranked first. The keywords green and ecosystem ranked high (2nd–3rd) in the first period, but their rankings dropped to 7th–8th over time. The keyword service also steadily dropped in ranking from the 6th to the 14th. Meanwhile, the keyword water remained consistently high within the top four. It is important to note that the keywords, such as climate and change, were ranked between 10th and 11th in the first period, and their rankings became higher over time, taking the 2nd and 4th places, respectively, in the third period. The keyword carbon appeared within the top 20 in the third period. Other keywords appeared and disappeared from the rankings, but most maintained similar rankings.

3.2.2 Keyword network

To analyze the keyword network, the size of the nodes was expressed with (1) the degree centrality and (2) the betweenness centrality of keywords. As mentioned earlier, degree centrality increases when a keyword has many direct links to other keywords, while betweenness centrality increases when a keyword frequently

appears on the shortest path between two different keywords in the network (Freeman, 1979; Freeman et al., 1991). In both networks, the thickness of links became stronger as the co-occurrence frequency of the connected keyword pair increased. The evolutions of keyword networks were also compared by dividing the periods starting in 2017 by 2 years.

In the network based on degree centrality, the node sizes of keywords became increasingly similar over time, and various links became thicker (Figure 8). In the first period, the node size of urban was remarkably larger, while that of other keywords was relatively smaller. The thick links were mostly connected to urban (e.g., urban-area, urban-water, urban-green, urban-climate, and urban-infrastructure), whereas the rest were thinner. During the second period, the node size of urban was still larger than other nodes, although it was less than in the first period, followed by water. Compared to the first period, the links connected to urban and those not connected to urban became thicker. The third period showed more remarkable changes than the first two periods; the node size of urban became smaller, whereas that of other keywords became larger to a level similar to that of urban. The links connected to urban and other links (e.g., carbon-forest, climate-climate, and flood-risk) became thicker. In summary, compared to the first two periods, when urban had the strongest influence in terms of degree centrality and co-occurrence frequency, the third period saw that the degree centrality of urban decreased, whereas that of other keywords became larger. The co-occurrence frequency pairs appeared diversely. Especially in the third period, the degree centrality of climate and change significantly increased, and simultaneously, that of carbon appeared in the rankings, and that of forest reappeared in the rankings (Table 4). In general, the frequency of all keywords significantly increased from the first period (2017–2018), the second period (2019–2020), and the third period (2021–2022), reflecting the steady increase in research papers on NbS.

In the network based on betweenness centrality, the same phenomenon was found: the node size concentrated in urban decreased over time, the node of water had the next highest size, and various links became thicker over time (Figure 9). However, unlike the results for degree centrality, the betweenness centrality of most of the keywords did not increase. Only the betweenness centrality of carbon and climate considerably increased over time. Another difference is that soil was ranked high regarding betweenness centrality during the entire period (Table 5).

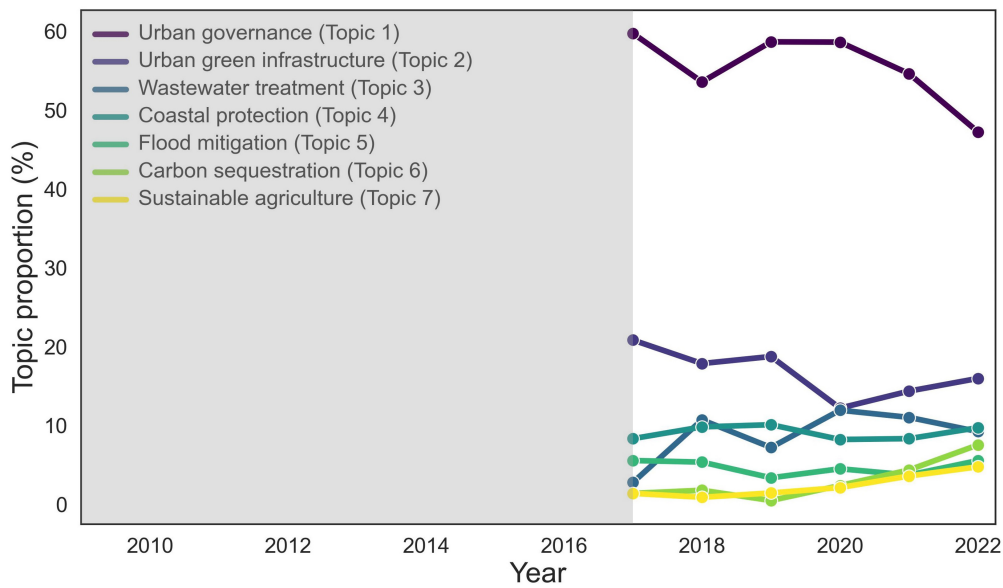


FIGURE 7 The ratio of the number of papers of each topic over the total number of papers (i.e., topic proportion) classified by latent Dirichlet allocation (LDA) topic modeling from 2017 to 2022.

TABLE 3 Keyword frequency during the first period (2017–2018), second period (2019–2020), and third period (2021–2022).

Rank	First period (2017–2018)		Second period (2019–2020)		Third period (2021–2022)	
	Keyword	Count	Keyword	Count	Keyword	Count
1	Urban	569	Urban	1,654	Urban	4,102
2	Green	227	Water	632	Climate	1,805
3	Ecosystem	223	Green	517	Water	1,762
4	Water	176	Ecosystem	499	Change	1,597
5	Area	175	Environmental	492	Area	1,425
6	Service	172	Climate	414	Environmental	1,394
7	Environmental	170	Sustainability	399	Ecosystem	1,376
8	Management	164	Area	399	Green	1,374
9	Sustainability	145	Change	392	Sustainability	1,174
10	Change	139	Management	371	Management	1,137
11	Climate	108	Infrastructure	350	Flood	967
12	Natural	105	Service	347	Benefit	954
13	Infrastructure	100	Benefit	317	Carbon	926
14	Society	99	Society	308	Service	881
15	Land	95	Development	287	Society	873
16	Soil	92	Natural	287	Development	858
17	Health	90	Flood	285	Natural	817
18	Value	88	Coastal	281	Risk	813
19	Risk	88	Ecological	280	Soil	803
20	Benefit	87	Risk	273	Ecological	792
Total	-	3,025	-	8,511	-	25,038

Keyword(s) whose frequency ranking(s) (1) remain on the top over time are marked by yellow; (2) decrease over time are marked by blue; (3) increase over time are marked by orange; and (4) appears in the third period is marked by green.

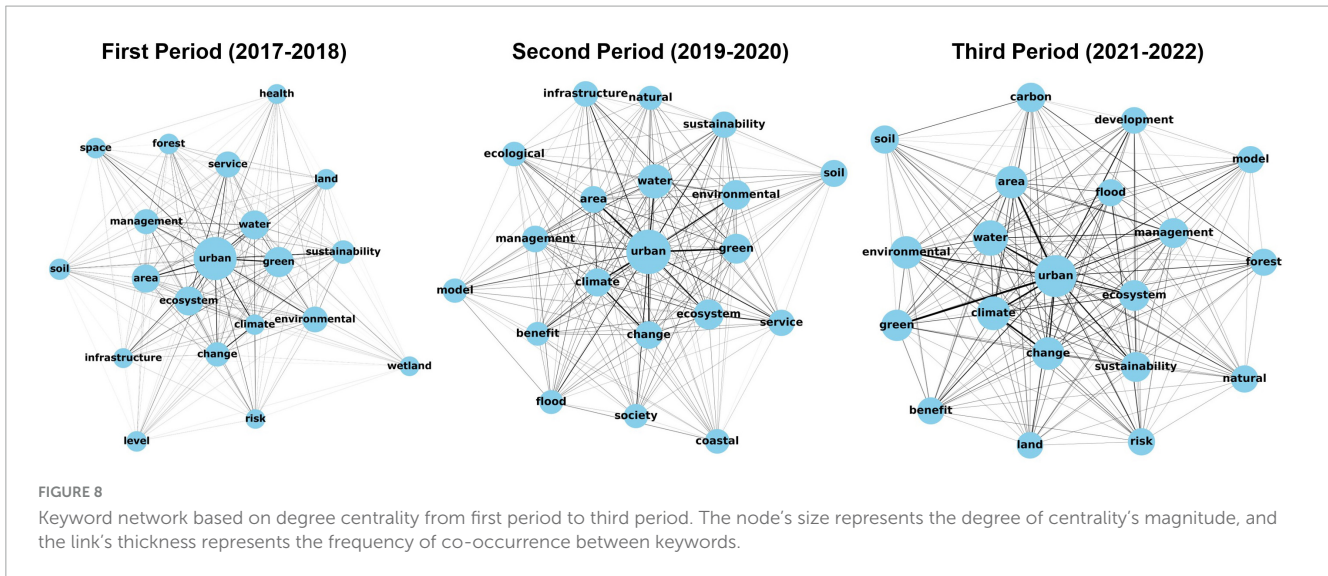


TABLE 4 Degree centrality during the first period (2017–2018), second period (2019–2020), and third period (2021–2022).

Rank	First period (2017–2018)		Second period (2019–2020)		Third period (2021–2020)	
	Keyword	Degree centrality	Keyword	Degree centrality	Keyword	Degree centrality
1	Urban	0.59	Urban	0.53	Urban	0.48
2	Green	0.29	Water	0.31	Water	0.34
3	Ecosystem	0.26	Ecosystem	0.24	Climate	0.30
4	Water	0.26	Green	0.24	Change	0.29
5	Area	0.25	Environmental	0.24	Environmental	0.28
6	Service	0.21	Climate	0.21	Area	0.28
7	Environmental	0.21	Change	0.20	Green	0.26
8	Management	0.19	Soil	0.19	Ecosystem	0.25
9	Change	0.18	Area	0.19	Sustainability	0.24
10	Sustainability	0.17	Management	0.19	Management	0.24
11	Soil	0.14	Service	0.18	Carbon	0.23
12	Space	0.13	Sustainability	0.18	Soil	0.21
13	Forest	0.13	Infrastructure	0.17	Natural	0.20
14	Level	0.13	Coastal	0.16	Risk	0.20
15	Land	0.13	Ecological	0.16	Forest	0.19
16	Climate	0.13	Society	0.16	Flood	0.19
17	Infrastructure	0.12	Model	0.16	Benefit	0.19
18	Health	0.12	Natural	0.15	Model	0.19
19	Wetland	0.12	Flood	0.15	Development	0.19
20	Risk	0.12	Benefit	0.15	Land	0.19

Keyword(s) whose degree centrality ranking(s) (1) remain on the top over time are marked by yellow; (2) increase over time are marked by orange; and (3) (re)appears in the third period is marked by green.

4 Discussion

As a result of analyzing research trends while targeting articles published since the term NbS was first officially utilized, it was possible to examine which research has received attention

and which research topic is likely to be more studied in the near future. This study also found that when topic modeling and keyword analysis were performed on the same literature dataset, two results delivered a consistent message and could complement each other.

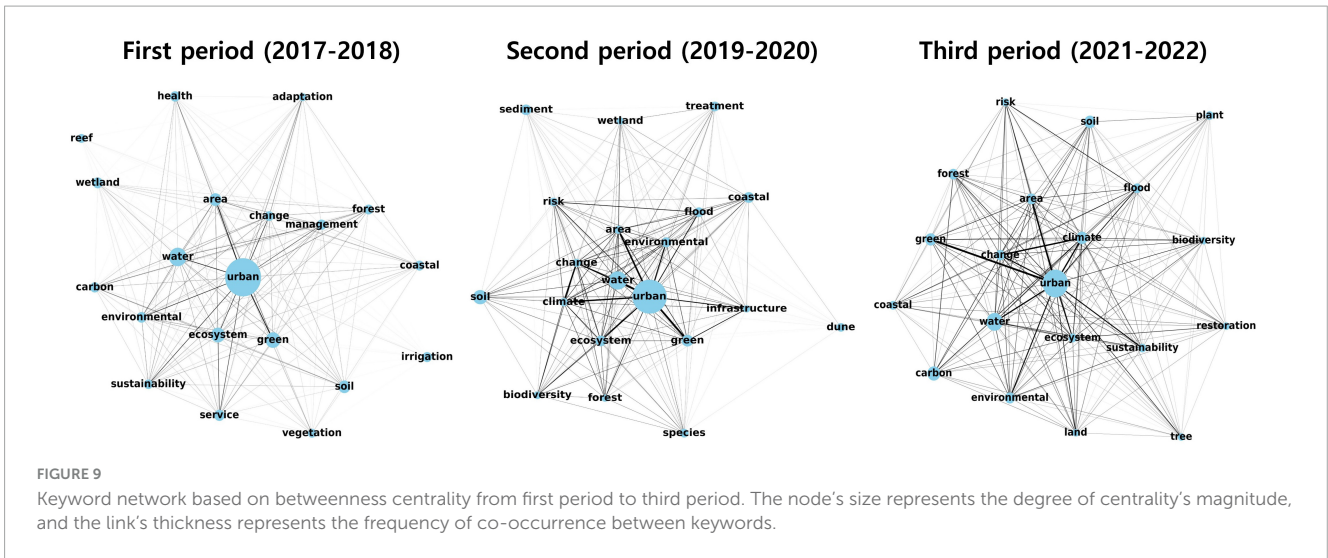


FIGURE 9 Keyword network based on betweenness centrality from first period to third period. The node's size represents the degree of centrality's magnitude, and the link's thickness represents the frequency of co-occurrence between keywords.

TABLE 5 Betweenness centrality during the first period (2017–2018), second period (2019–2020), and third period (2021–2022).

Rank	First period (2017–2018)		Second period (2019–2020)		Third period (2021–2020)	
	Keyword	Betweenness centrality	Keyword	Betweenness centrality	Keyword	Betweenness centrality
1	Urban	0.42	Urban	0.35	Urban	0.22
2	Water	0.09	Water	0.10	Water	0.09
3	Green	0.07	Soil	0.06	Carbon	0.06
4	Ecosystem	0.06	Green	0.04	Soil	0.04
5	Area	0.04	Coastal	0.03	Climate	0.04
6	Soil	0.04	Ecosystem	0.03	Green	0.04
7	Service	0.03	Sediment	0.03	Environmental	0.03
8	Wetland	0.03	Environmental	0.03	Area	0.03
9	Environmental	0.03	Flood	0.03	Forest	0.03
10	Health	0.03	Treatment	0.03	Change	0.03
11	Management	0.03	Species	0.02	Flood	0.02
12	Carbon	0.03	Dune	0.02	Ecosystem	0.02
13	Irrigation	0.03	Risk	0.02	Coastal	0.02
14	Coastal	0.03	Climate	0.02	Plant	0.02
15	Forest	0.03	Area	0.02	Sustainability	0.02
16	Change	0.03	Change	0.02	Risk	0.02
17	Sustainability	0.02	Biodiversity	0.02	Biodiversity	0.01
18	Vegetation	0.02	Forest	0.01	Tree	0.01
19	Reef	0.02	Wetland	0.01	Land	0.01
20	Adaptation	0.02	Infrastructure	0.01	Restoration	0.01

Keyword(s) whose betweenness centrality ranking(s) (1) remain on the top over time are marked by yellow; and (2) increase over time are marked by orange.

4.1 Trends of topics: big urban and water, small but increasing carbon and agriculture

Since the first appearance of the NBS term, most research has focused on cities (Topic 1, 2) and water (Topic 3, 4, 5) (Figures 5, 6). Still, this study found a significant increase in the proportions of

carbon sequestration research (Topic 6) and sustainable agriculture research (Topic 7) recently, with larger increases (Figure 7). The increase in the proportion of carbon sequestration research became larger than the increase in water research between 2021 and 2022. If the former research maintains the same tendency as now, it is expected to overtake the proportion of water-related topics in the near future. The findings of this study suggest that urban and water-related research has been overwhelmingly dominant in the NBS

research. Still, despite being less common, carbon sequestration and sustainable agriculture research has increased significantly and may become more active soon.

The findings of this study are consistent with those of other studies that partially examined research trends in NbS. For example, [Parker et al. \(2020\)](#) conducted a quantitative literature review on NbS. They found that NbS was initially studied in traditional research fields such as ecosystem management; however, recently, it was more likely to serve as a specific mechanism in response to climate change. [Su et al. \(2023\)](#) emphasized that ecosystem services, climate change, and sustainability have recently been intensively studied in the NbS research on urban wastewater management, which was clarified by a bibliographic literature review. However, neither study could specifically explain what proportion each field accounts for and how it changes over time, while this study provided a quantitative ground for their arguments by showing increases in the proportions of carbon sequestration and sustainable agriculture among NbS research areas through topic modeling.

4.2 Trends of keyword: more diverse keywords have been appeared beyond urban

As a result of the keyword analysis, as for the keyword frequency, urban was the most frequent keyword during the periods, but the frequency of diverse keywords increased over time; particularly, the frequency of climate and carbon remarkably increased. On the other hand, as for the network based on co-occurrence frequency, (1) in the case of degree centrality, during the first period, the node size of urban was large, but that of other keywords was small, and thick links were mostly connected to urban. However, as we moved on to the third period, the node size of urban became smaller, whereas that of other keywords became larger (especially climate and change), and links between various keywords became thicker ([Figure 8](#)). These results imply that the co-occurrence frequency of keywords including not only urban but also climate, change, carbon, and forest became higher over time, and there has been more interest in various fields (particularly climate change) rather than just limiting to the previously dominant urban field. (2) In the case of betweenness centrality, the results were similar to degree centrality, with urban being the highest in all periods. Still, there are differences in that the node size of urban decreased, whereas that of other keywords did not increase, except for such keywords as carbon and climate. There was another difference in the consistently high ranking of soil after water ([Figure 9](#)). These outcomes indicate that keywords such as urban, water, and soil have been consistently important in mediating the shortest distance between different keywords, and the role of carbon and climate has become relatively more important over time.

This tendency in which the frequency of carbon or climate increases, or the connection with other keywords becomes dense in the NbS research, is a new result that has never been reported in previous studies. For example, [Nyika and Dinka \(2022\)](#) analyzed keywords in NbS articles targeting Africa over the past decade and found that climate change most frequently appeared along

with conservation, governance, and South Africa. There were close connections with other keywords, but they could not show whether there was an increasing trend, as they did not make a comparison per period. [Mendes et al. \(2020\)](#) also analyzed the keywords from 132 articles on NbS and found that climate change had the highest connection with NbS, after ecosystem service, but could not show an increasing trend over time.

As shown in this study, the findings that the frequency of carbon or climate increased over time, and the connections with other keywords also increased, reflect the current situation in which there has been a growing interest in NbS in the last decade as a means to reduce GHGs causing climate change ([Seddon et al., 2020](#)). Furthermore, Nationally Determined Contributions (NDC), which are GHGs reduction targets that were voluntarily set by each country to meet the goals of the Paris Agreement and were applied after 2020, have become more important. As the most NDCs recognized NbS as a means to mitigate and adapt to climate change impacts ([Seddon et al., 2019](#)), it can be assumed that NbS has recently become solidified its position as a means to reduce GHGs.

4.3 Limitations and lessons-learned from this study

The two (i.e., topical modeling and keyword analysis) methods used in this study have their own limitations. First, topic modeling assumes that one research paper has only one topic, which is not always true. For example, restoring mangrove forests along the coast could prevent coastal erosion but could also be interpreted as mitigating GHGs by sequestering carbon. However, topic modeling cannot handle the multifunctional features of NbS research, which may cover more than two topics, because each article was assigned to only one topic with the highest probability of being assigned. Instead, by assigning articles to the corresponding topic, it makes it possible to calculate the proportion of the corresponding topic in the entire research. On the other hand, keyword analysis can reflect the multifunctional phenomenon of simultaneously using multiple keywords in a single paper by analyzing the frequency of keywords or the co-occurrence frequency of keyword pairs. Still, it is difficult to analyze the results by matching the number of papers.

To compensate for the limitations of each method, this study both analyzed how the number of articles corresponding to each topic changed over time at a topic level using topic modeling and analyzed how the frequency and co-occurrence frequency of each keyword changed over time at a keyword level using keyword analysis. As a result, those two methods, with approaches to NbS research at topic and keyword levels, conveyed a consistent message that there has been an increase in recent interest in carbon and climate change. Therefore, this study confirmed that these two methods are complementary while bringing more confidence in the findings of this study.

However, as increased academic research on carbon or climate in NbS does not always guarantee success in policies (e.g., [Seddon et al., 2021](#); [Viti et al., 2022](#)). Beyond the academic realm, in which there have been more studies on NbS to respond to climate change, there should be political and technical support to contribute to solving climate change issues practically in reality. To this end, it

will be necessary to increase the value of NbS in mainstreaming climate change policy and the application and effectiveness of climate technology. Additionally, since NbS is multifunctional and interdisciplinary, it should be researched as a Nexus between climate change and other areas (e.g., city, water, and food).

5 Conclusion

This study quantitatively analyzed the global research trends in NbS over the last 13 years through topic modeling and keyword analysis. Such attempts helped to understand how NbS has been promoted in which fields to address social issues. This study confirmed that NbS has been researched in governance and infrastructure building to solve urban issues, various measures to solve water problems such as wastewater, coastal erosion, flooding, carbon sequestration to address climate change, and agriculture for sustainable coexistence with biodiversity. While NbS has been mainly focused on solving urban and water-related issues, it has been gradually expanding to other fields based on the connections with NbS; especially, carbon sequestration in response to climate change was confirmed to be the fastest-growing field. These results imply that carbon sequestration and responses to climate change will be more researched in NbS in the near future. Additionally, this result confirmed that topic modeling and keyword analysis, which have limitations when used individually, are complementary to each other when used together.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HY: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review

& editing. JC: Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. CS: Writing – original draft, Writing – review & editing. EC: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/ffgc.2024.1351189/full#supplementary-material>

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