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Mainstreaming nature-based solutions for sustainable agriculture:
linking global evidence to scaling and governance

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E-mail: 3064461J@student.gla.ac.uk**Keywords:** nature-based solutions, sustainable agriculture, ecosystem services, climate co-benefits, NbS governanceSupplementary material for this article is available [online](#)**Abstract**

Agriculture plays a significant role in driving greenhouse gas emissions and biodiversity loss. Although nature-based solutions (NbS) in agriculture are recognised as a holistic way to achieve long-term sustainability of food systems and climate goals, global understanding of the drivers and barriers to large-scale implementation of NbS in sustainable agriculture remains limited. Here, we employ sustainable agricultural approaches, as recognised by the International Union for Conservation of Nature, as a typology for classifying evidence of NbS implementation in agriculture. We systematically review 171 articles to identify barriers and enablers, including governance, ecological settings, and climate co-benefits, which influence their implementation. While NbS in agriculture offer opportunities for food security, ecosystem services, climate co-benefits, and sustainable development, our analysis reveals that most remain geographically uneven, small-scale, and primarily publicly funded. We identify two main features of the current agricultural NbS landscape: development-driven archetypes, mostly in low- and middle-income countries, that focus on food security and productivity improvement; and post-industrial or social-benefit archetypes in higher- to upper-middle-income countries that emphasise urban agriculture, quality of life, and biodiversity. We found top-down NbS governance and a lack of cross-sector collaboration, which may hinder its scaling. We contend that achieving inclusive and more robust NbS in agriculture necessitates attention to more private financiers, regional context, local governance, and targeted co-benefits.

1. Introduction

Global agricultural production needs to expand to 14 060 trillion crop calories, approximately a 47% increase relative to the 2011 level, to meet the food demand of 9.75 billion people by 2050 (Ron Sands 2023). High-input conventional agriculture can contribute to greenhouse gas (GHG) emissions, which alter the carbon, water and nitrogen cycles, resulting in a loss of farmland productivity and biodiversity (Dalin and Rodríguez-Iturbe 2016, Ilampooranan *et al* 2022). Thus, achieving this target requires ensuring sustainability and doubling agricultural productivity, as envisioned by the United Nations Sustainable Development Goal, SDG 2 on zero Hunger. Advances in plant breeding practices, fertilisation, irrigation, and integrated

pest management have increased the global yield of major crops per unit of land area by 2.5–3 times since 1960 (Intergovernmental Panel on Climate Change (IPCC) 2023a). Nevertheless, agriculture remains one of the major drivers of climate change through GHG emissions and land-use change (Lamb *et al* 2021, Cerutti *et al* 2023), while being highly vulnerable to its effects, worsening food insecurity and ecological degradation (IPCC 2023a). Climate change reduces crop yields to varying extents across crop types and regions (Porter *et al* 2019, Sultan *et al* 2019, Brás *et al* 2021). Between 1991 and 2021, extreme temperatures (25%), drought (20%), and floods (15%) were the most significant hazards affecting crops and livestock production worldwide (FAO 2023).

Sustainable agricultural development is essential to promote an inclusive global economic growth

while balancing land use demands between agriculture (SDG 2) and ecological integrity (SDG 15) (Meijaard *et al* 2020, Piñeiro *et al* 2020). To achieve this balance, diverse climate mitigation and adaptation strategies are being implemented (IPCC 2023a, 2023b), protecting nature's regenerative capacity and ecological integrity (European Environment Agency (EEA) 2023). Sustainable agricultural systems aim for 'win-win' outcomes that satisfy human needs and enhance well-being while simultaneously benefiting ecosystems (Rasmussen *et al* 2018). In this context, the concept of a nature-based solution (NbS) has been endorsed by the International Union for Conservation of Nature (IUCN), clarifying its definitional framework and core principles in 2016 (Cohen-Shacham *et al* 2019).

NbS may offer a pathway to sustainable agriculture by reducing GHG emissions, enhancing biodiversity, and building resilience to climate change (Fuller *et al* 2005, Singh *et al* 2014, Catarino *et al* 2019, Das *et al* 2019, Gugissa *et al* 2022, Kirsop-Taylor and Russel 2022, Risna *et al* 2022, Do *et al* 2023, King *et al* 2023, Brown *et al* 2024, Anand *et al* 2025, Yue *et al* 2025). They are also recognised as practices that protect, conserve, restore, sustainably use, and manage agricultural ecosystems while addressing socioeconomic and environmental challenges effectively and adaptively (Demozzi *et al* 2024). In recent years, increasing academic attention to NbS reflects the need to understand and strengthen their social-ecological sustainability (Cohen-Shacham *et al* 2019, Giudice Badari *et al* 2020, Abd-Alla *et al* 2023, Lange *et al* 2023, Srivastava and Bharti 2023, Kaboré *et al* 2024).

A diverse range of social-ecological benefits of NbS in agriculture, such as agroforestry (Kaboré *et al* 2024), crop rotation (Gugissa *et al* 2022), cover cropping (Cerdà *et al* 2022), grazing management (Noulékoun *et al* 2021) and urban agriculture (McGreevy *et al* 2022), has been widely reported. While NbS offers a blueprint for transforming agricultural food production and guiding climate action, its widespread, large-scale implementation has yet to be achieved (Anon 2023, Miralles-Wilhelm 2023, Regmi and Gheewala 2025). Recent syntheses of global NbS evidence have generally focused on specific intervention types, aiming to achieve particular co-benefits (Ewert *et al* 2023, Nguyen *et al* 2024), or on their integration across multiple objectives, such as food production, conservation, and climate mitigation (Miralles-Wilhelm 2023). Nevertheless, systematic insights into the factors limiting large-scale NbS implementation in agriculture remain largely unexamined.

Through a systematic literature review, synthesis and analysis, we develop a global-scale comprehensive understanding of the fragmented evidence that impedes the scaling of NbS in this sector. In this

context, we identify key enabling factors and examine the dynamic interactions among variables, including financing, institutions, policy factors, awareness and knowledge that influence social-ecological sustainability (Regmi and Gheewala 2025). The recurring pattern of NbS characteristics that capture ecological, social, and institutional dimensions across NbS cases can be understood as a broader system configuration that reveals which strategies effectively support successful scaling. To this end, we address the following research question: (1) what does the current global literature reveal for agricultural NbS implementation regarding their geography, institutional patterns, and ecological settings? (2) How do these characteristics across NbS types combine into a broader system configuration which reveals scaling strategies? (3) How can current localised policies across diverse regions be reshaped to scale up NbS for both mitigation and adaptation outcomes? We selected these research questions due to a persistent implementation gap in NbS in agriculture and a lack of evidence on how NbS reinforce the social-ecological benefits (Cohen-Shacham *et al* 2019). Moreover, our understanding of how governance mechanisms influence large-scale NbS implementation remains limited (Petzold *et al* 2023). Here, we present the findings of a systematic assessment of global evidence on NbS in agriculture, highlighting the barriers and pathways for a large-scale implementation.

2. Methods

2.1. Methodological framework

We employed a typology, a structured classification framework, to systematically review and classify complex NbS in agriculture. This approach groups cases based on common attributes that support meaningful comparison among cases (Kluge 2000). This classification serves as a preliminary step in organising NbS cases systematically prior to further analysis. In this study, we employed IUCN's sustainable agricultural approaches for systematically categorising NbS interventions in agriculture. It encompasses 14 approaches to sustainable agriculture (Demozzi *et al* 2024). The choice of categorisation primarily depends on the specific aim of the intervention type and the relevant ecological function of the sustainable agricultural approach. IUCN further asserted that these 14 sustainable agricultural approaches align with its global standards for NbS. These standards consist of 8 criteria, including addressing different societal challenges (criterion 1), informed by the scale and jurisdictional context (criterion 2 and 8), biodiversity net gain and ecological integrity (criterion 3), economic viability (criterion 4), inclusive governance (criterion 5), potential trade-offs between the primary objective and co-benefits (criterion 6), and criterion 7

on ensuring an adaptive management plan. Detailed guidance on how each of these sustainable agricultural approaches aligns with NbS principles has been widely reported in the literature (Demozzi *et al* 2024).

We adopted a systematic approach, which uses pre-defined theories or existing findings to identify key concepts or variables that support initial coding categories of analysis (Roy *et al* 2025). We included studies documented in highly citable databases, such as Elsevier's Scopus, Web of Science, and SAGE bibliographic databases, with a particular emphasis on the use of NbS interventions to address climate change mitigation and adaptation in agriculture. The 2020 'Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)' statement protocol was adopted for the process of literature identification, screening, and selection (Page *et al* 2021a, Taiyebi *et al* 2025). We analysed the articles' content, revealing connections between articles and pre-defined themes.

2.2. Screening and data extraction

This study employed the PEO framework (van 2025, Hosseini *et al* 2024, Ahmed *et al* 2025). As a comprehensive search strategy (supplementary material I, table S1). The PEO framework is commonly used to formulate qualitative research questions (Methley *et al* 2014) and it ensures that research questions cover all relevant elements. The PEO framework clearly defines the population or group of participants (farming or agricultural community, farming or agricultural system), exposure (NbS or natural climate solutions, climate-resilient farming), and outcome (livelihood improvement, resilience, adaptive capacity, food security improvements). The framework helps narrow down broad contextual themes into specific research questions, ensuring alignment with the research aims. Moreover, it supports narrative synthesis by providing a consistent basis for comparing studies and identifying patterns and gaps in the literature.

Since this study focuses on NbS interventions in agriculture and their outcomes, it excludes criteria that are not relevant, such as conventional or industrial agricultural approaches, as well as issues related to diseases and pollution in agriculture. We identified all relevant studies published up to the date of the literature search (20 December 2024), including preprints, using a query string across the article title, abstract, and keywords. The search keywords consisted of 62 criteria for inclusion and 15 for exclusion (supplementary material I, table S1). These inclusion criteria included 22 keywords related to the population (agricultural or farming communities), 14 representing exposure (NbS or natural climate solutions, climate change mitigation and adaptation measures), and 26 focusing on the outcome (socio-ecological benefits and trade-offs). Only peer-reviewed articles written in English were selected for the study.

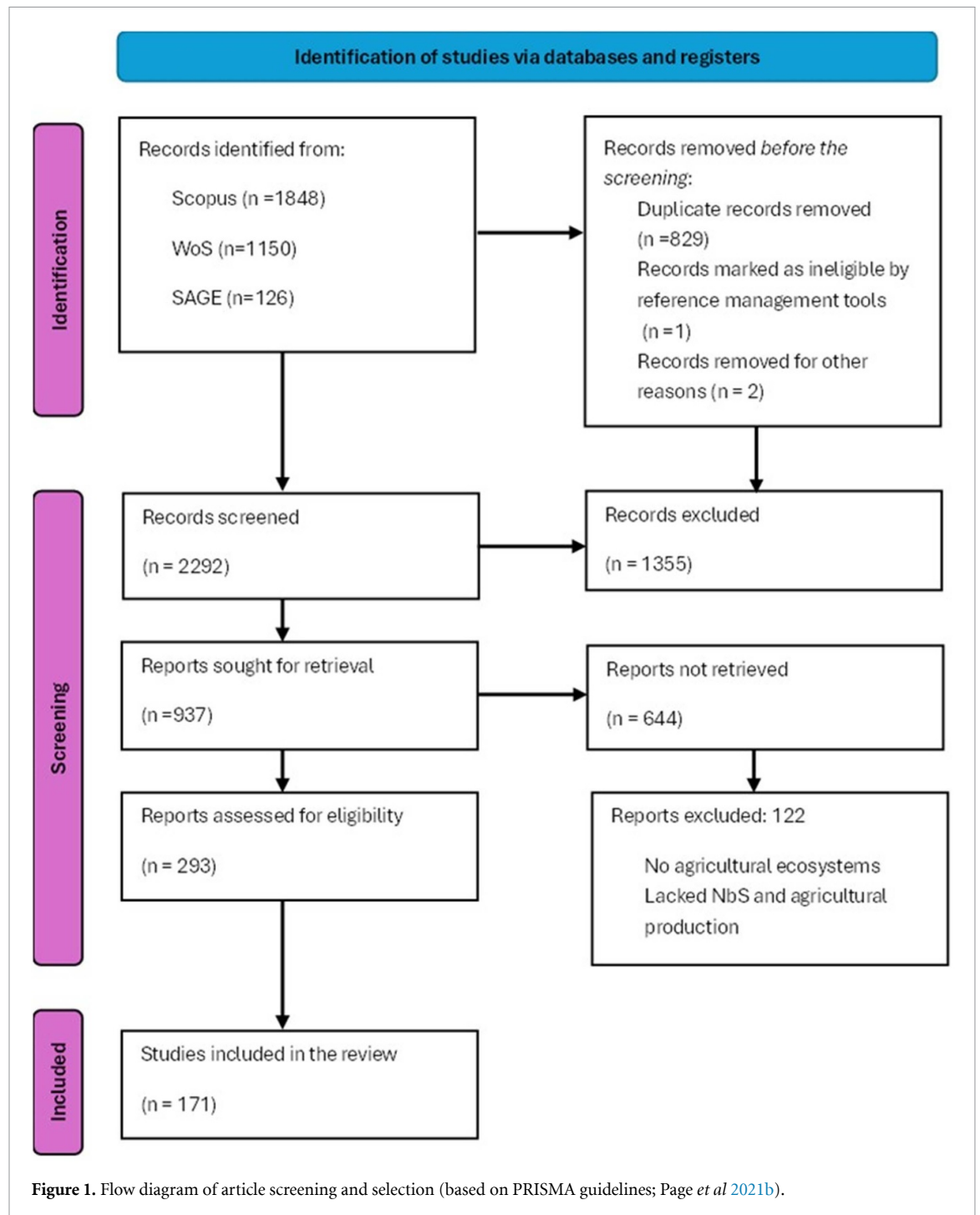
We selected 937 peer-reviewed articles for retrieval based on their titles and abstracts after initially screening 2292 articles, excluding those not relevant to NbS in agriculture. To ensure more rigorous and consistent inclusion criteria, we adopted IUCN's working definition of NbS when selecting relevant articles for the in-depth review. We included NbS agricultural practices when they met any of these inclusion criteria, which were broadly identified under the ecosystem basis (restore or maintain soil biotic function, micro-climate, pollinator services, water retention, vegetation cover), address societal challenges (yield stability, soil erosion, drought risk, climate mitigation and adaptation), biodiversity gain, and ecosystem services (ES) (ecological co-benefits, production outcomes), as well as evidence of effectiveness or adaptiveness (monitoring or evidence for social-ecological indicators) (Cohen-Shacham *et al* 2016).

We excluded articles that did not meet the inclusion criteria mentioned above, including those that did not specifically address the agricultural production landscape. Moreover, we did not retain studies that examined farmers' attitudes or awareness of NbS in agriculture without focusing on specific NbS measures or their outcomes. Excluded articles were manually re-evaluated using their title and abstracts to minimise biases and ensure that relevant articles were not mistakenly excluded in the screening process. In the next stage, we excluded duplicate articles and review articles from the list, and 293 articles remained for the in-depth review (figure 1).

Finally, we included 171 articles in the content analysis, excluding 122 articles that did not focus on agricultural ecosystems and lacked specific NbS interventions. Considering each article as a case in this study, we extracted the geographic location of the study, the climatic classification of the study area, ES provided by each sustainable agricultural approach, aligned SDG targets, climate adaptation and mitigation measures, key actors, and citation information from the examined articles (supplementary material I, table S2: criteria for extracting the content).

2.3. Data analysis

We analysed 171 articles using thematic analysis to identify geographical, institutional and ecological patterns across them, thereby addressing the first research question. The key dimensions identified in the analysis include geographic and climatic distributions, actor types and their roles, ES, alignment with the United Nations SDGs, and climate mitigation and adaptation measures. To explore the geographic and climatic distributions of NbS studies, we compiled global evidence of NbS interventions in agriculture across countries and joined it with the world-country shapefile using the common attribute of country names. The number of studies was then symbolised proportionately, and spatial mapping was



carried out using ArcGIS Pro 3.3 (available from Esri, www.esri.com/en-us/home). Article screening was conducted using Zotero, a reference management software. We analysed ES provision within each sustainable agricultural approach following the millennium ecosystem assessment because it is a widely recognised, comprehensive classification (Leemans and de Groot 2003). The associated SDGs and NbS studies were analysed using the SDG targets listed by the United Nations (available at https://sdgs.un.org/#goal_section). We systematically assessed NbS studies against climate mitigation and adaptation measures as emphasised by the IPCC (IPCC 2023a,

2023b). The Python ‘Plotty’ library and Microsoft Excel were used in preparing the interactive graphs presented in this study.

We employed archetype analysis to examine multidimensional, recurrent patterns in NbS studies to identify a broader system configuration. It is a rule-based configurational synthesis (Oberlack *et al* 2019) and is increasingly recognised as a method for identifying recurrent patterns of variables across a given social-ecological system (Václavík *et al* 2013, Levers *et al* 2018, Vidal Merino *et al* 2019, Wicki *et al* 2023). In our archetype analysis, we used attributes identified in the thematic analysis (e.g. geography, involved

actors, ES, climate mitigation and adaptation, SDG targets) at the intermediary level of abstraction to capture broader patterns. Based on the archetypes identified in the analysis, we suggest reshaping policies to scale up NbS in agriculture that are tailored to the distinctive characteristics of NbS cases.

Conversely, several methodological limitations are worth highlighting here. We included broader search terms relevant to NbS, such as ecosystem-based climate mitigation and adaptation, to address the heterogeneity of NbS terminology in agriculture. We used highly cited databases to retrieve documented evidence; however, additional practices may be reported elsewhere. Additionally, we classified NbS under sustainable agricultural approaches according to their specific aim of intervention, and the evaluation of each type is case-specific. Nevertheless, some practices identified in this study can be aligned with multiple sustainable agricultural approaches due to their multidimensional nature. Furthermore, the inclusion of certain practices is case-specific, consistent with the NbS concept. For example, some rainwater-harvesting and minor irrigation practices included in this study align with the NbS concept by enhancing biodiversity; however, this is not always the case for all irrigation practices.

3. Results

3.1. Global evidence landscape of NbS in agriculture

3.1.1. Typological and geographical patterns of NbS in agriculture

We identified 171 articles documenting NbS in agriculture from 2002 to 2024, which met our inclusion criteria and indicate a positive trend over the past two decades (supplementary material I, figure S1). Following the IUCN guidelines for NbS and sustainable agricultural approaches, we identified 10 major groups of NbS applications and associated them with 14 distinct sustainable agricultural approaches. These major NbS groups were based on agricultural management practices and comprised 44 distinct NbS practices. Agroecology (AG, 49 studies) and regenerative agriculture (RA, 32 studies) are the most prevalent. Approximately one-third of NbS studies consist of agroforestry and tree-based systems (29.2% of articles), followed by soil and nutrient management (18.7%), grazing and pasture management (15.2%), and crop management and diversification (14.6%) (figure 2 and supplementary material I, table S3).

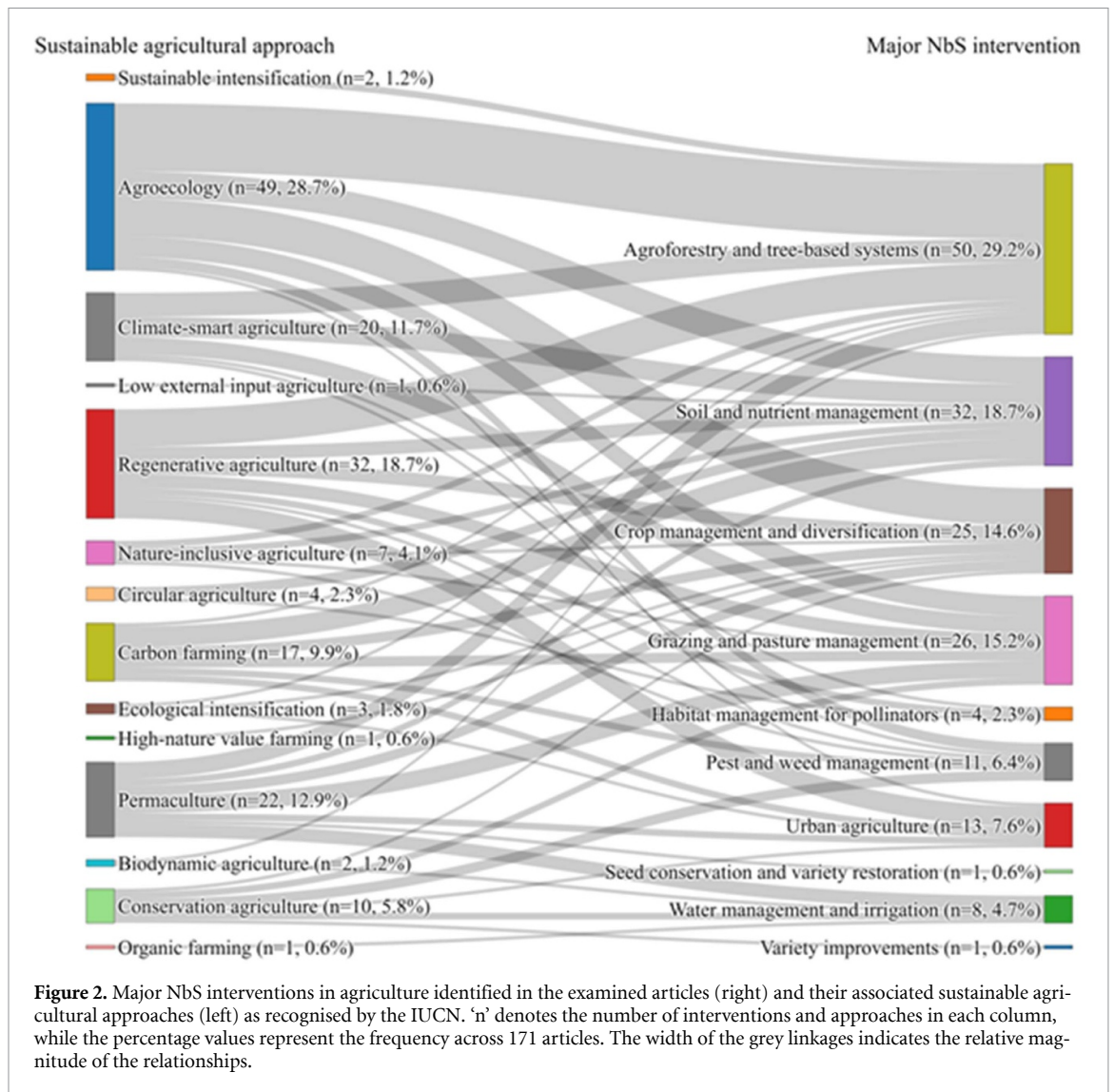
The spatial distribution of NbS studies in agriculture reflects the regional and climate patterns of NbS types being implemented (figure 3(a)). Our spatial mapping results revealed that evidence for NbS in agriculture is unevenly distributed across countries, with a notable geographic disparity. Most NbS

studies were conducted in Asia (44%), followed by Europe (25%) and Africa (11%). Moreover, NbS studies exhibit a climatic zone bias towards temperate (49%) and tropical (22%) zones, with fewer studies in other regions (figures 3(a) and (b)). For example, NbS in temperate regions were primarily concentrated in Europe and some highland areas, including Ethiopia, Kenya, the Himalayas, and the Chinese Loess Plateau.

3.1.2. Actors, multi-actor groupings and their roles in NbS interventions

Our analysis revealed which actors are involved in NbS in agriculture and which are more likely to contribute to specific intervention roles. We found asymmetric participation and persistent disconnect among actors in NbS interventions, highlighting a limited involvement of private sector financiers (6% of studies), while academia and individuals (households) were the most frequently reported actor types in terms of their presence across roles within NbS agriculture (98% and 67% respectively) (figure 4(a)). Academia and individuals were by far the most interconnected with other actors. Furthermore, national governments, the third most reported actor type (56%), were mainly associated with individuals (22%) in the NbS interventions. In contrast, we observed a few reported relationships involving NGOs, sub-national governments, sub-national civil society, and national civil society (all less than 5%) (figure 4(b)). Higher participation does not necessarily imply dominance across all roles. NbS in agriculture is characterised by a differential actor configuration, which is largely an academic-led assessment, centrally governed and primarily undertaken by individuals (figure 5). For example, NbS implementation is mainly led by individuals or households (67% of studies), supported by financing (43%) and planning (28%) from national governments, with academia involved in assessing NbS outcomes (96%) and monitoring contributions over time (30%). The frequent representation of academia, particularly in assessment roles, likely reflects its inherent role in assessment, thereby contributing to its prominence in academic literature. Within the governance framework, we observed that sub-national and local governments lack authority over budgeting (1%–3%) and coordination (14% and 20%, respectively) of NbS in agriculture.

We found relatively few studies providing evidence of the role of the large-scale private sector and small and medium enterprises in supporting implementation of NbS interventions (6% of studies) and their financing (1.2%). Encouragement for financing and further expansion of NbS in agriculture is often linked to awareness among various actors; however, our analysis did not find substantial evidence supporting the role of awareness, apart from



limited participation from individuals (18%) who have engaged in field experiments (Singh *et al* 2014, Gugissa *et al* 2022, Do *et al* 2023).

3.1.3. Linking the value of ES to scaling NbS

Among the ES provided by NbS in agriculture, regulatory (e.g. climate regulation), supporting (e.g. nutrient cycling, soil formation), and provisioning (e.g. food supply) services are often associated with NbS practices (Atallah *et al* 2018, Legaspi *et al* 2021, Kaboré *et al* 2024). NbS in agriculture that fall under agroecological approaches constitute the largest NbS category (49 articles) and report a wider range of ES, with climate regulation and nutrient cycling identified in about 15% of agroecological approaches. In contrast, most cultural services showed limited alignment with NbS studies (Barrow 2014, Amato and Simonetti 2021, Buxton *et al* 2021, Lovell *et al* 2021).

A diverse range of actors may be interested in ES linked to NbS to reduce the climate and biodiversity crisis while supporting sustainable agriculture. For example, RA (Quin *et al* 2015, Sanderson

et al 2020, Guo *et al* 2021) and organic agriculture (Fuller *et al* 2005) approaches primarily deliver nutrient cycling and soil formation supporting services, indicating more public benefits, such as soil health and ecosystem restoration, which are of most interest to the public and conservationists. In contrast, AG, permaculture, and climate-smart agriculture reveal a more diverse range of ES, encompassing wider social-ecological benefits (figure 6).

We did not observe a notable number of NbS practices linked to cultural services or air quality and disease regulatory services. The lack of such evidence is likely due to the limited prevalence of certain NbS practices that possess these inherent features (e.g. biodynamic agriculture). Moreover, some ES linked to NbS in agriculture indicate synergistic benefits with water flow regulation and erosion control. Under climate-smart agriculture (Neog *et al* 2016, Prasad *et al* 2024) and conservation agriculture (Sheoran *et al* 2022, Kissi *et al* 2023, Ogle *et al* 2023), there are shared co-benefits for the land and water sectors.

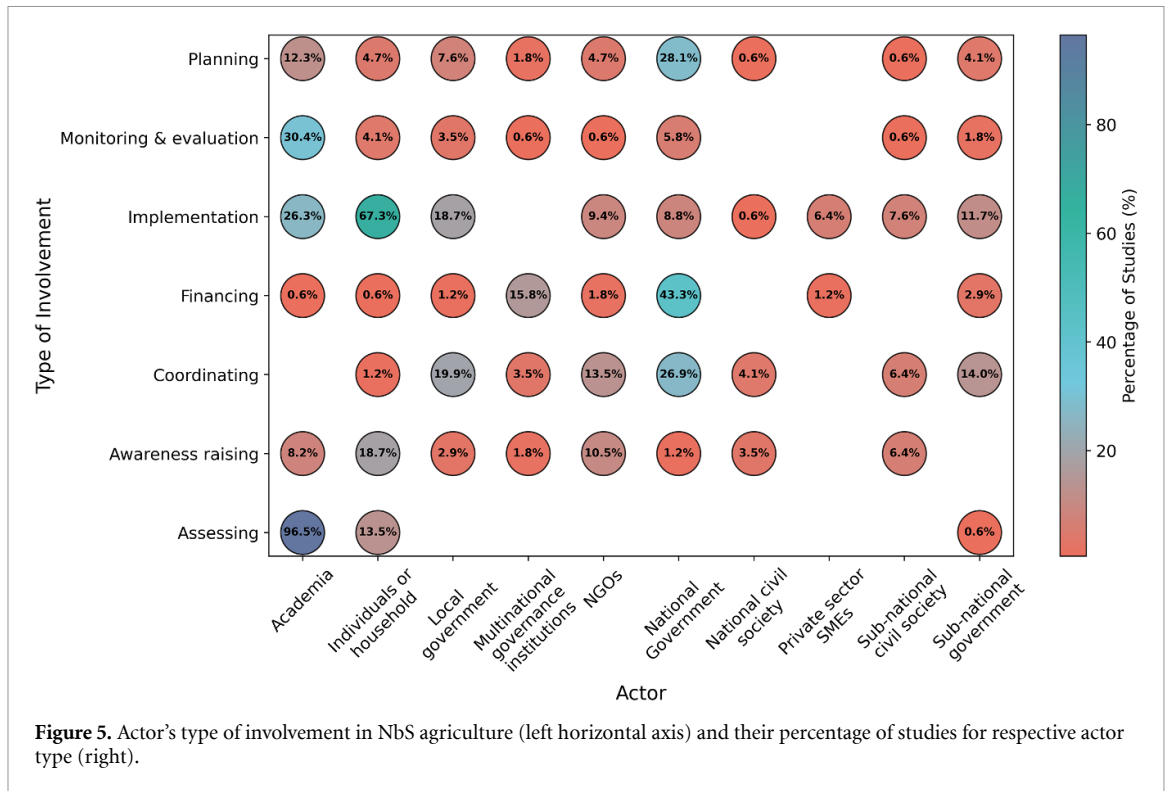


Figure 5. Actor's type of involvement in NbS agriculture (left horizontal axis) and their percentage of studies for respective actor type (right).

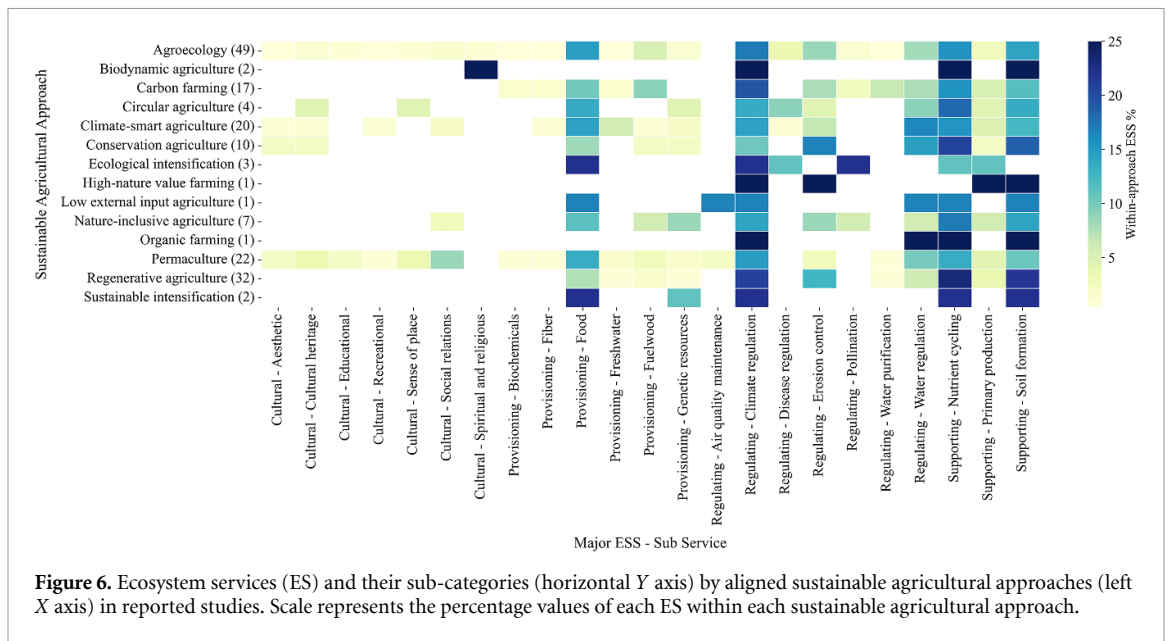


Figure 6. Ecosystem services (ES) and their sub-categories (horizontal Y axis) by aligned sustainable agricultural approaches (left X axis) in reported studies. Scale represents the percentage values of each ES within each sustainable agricultural approach.

3.1.4. Sustainability driven by NbS in agriculture

Our results revealed how NbS interventions align with the SDGs targets and whether existing NbS practices are moving towards right direction. For example, of the 171 studies, approximately half of them were consistent with the SDG target related to sustainable food production (Target 2.4), strengthen resilience and adaptive capacity (13.1), and restore degraded lands (15.3) (figure 7). Agroecological approaches, being the largest category of sustainable agricultural approaches linked to a range of SDG targets, including sustainable food production (Ngondya et al 2016,

Atallah et al 2018, Do et al 2023, Kaboré et al 2024), restore degraded lands (Juwarkar 2012, Das et al 2019, Legaspi et al 2021, Reang et al 2024), and strengthen resilience and adaptive capacity (Neog et al 2016, Varela et al 2022, Hazarika et al 2024).

Beyond this, we identified several additional notable approaches that contribute to the targets of SDGs 2 and 15. For example, grazing at optimal intensity and cultivated pastures are mainly linked to restoration (Quin et al 2015, Chen et al 2016, Gosnell et al 2020, Johansson et al 2021), while urban gardens, rooftop farming, and community forestry

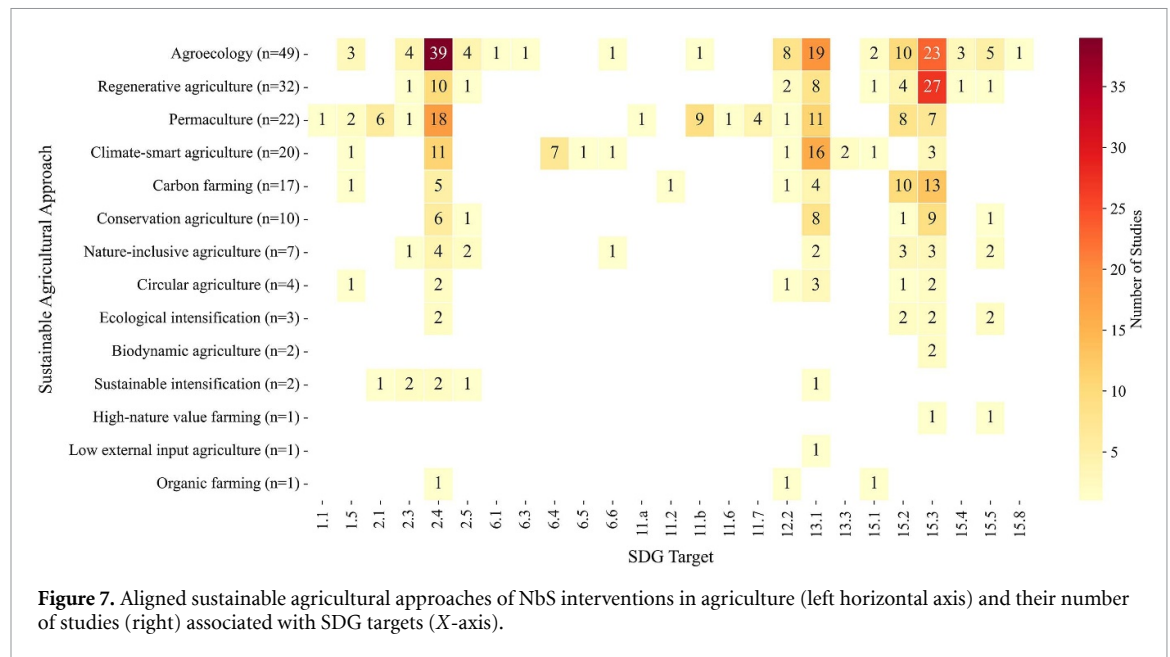


Figure 7. Aligned sustainable agricultural approaches of NbS interventions in agriculture (left horizontal axis) and their number of studies (right) associated with SDG targets (X-axis).

promote sustainable food production and help to ensure its availability (De Filippi et al 2019, Artmann et al 2020, Russo and Cirella 2020, Amato and Simonetti 2021).

3.1.5. Climate adaptation and mitigation as an NbS-scaling framework

In our analysis, we identified a wide range of adaptation and mitigation measures, consistent with those described in the IPCC (IPCC 2023a, 2023b) (figure 8). We observed that adaptation pathways are slightly more associated with NbS than mitigation outcomes. For example, when NbS fall under climate-smart agriculture, irrigation, and sustainable intensification, they mostly exhibit adaptation characteristics, whereas RA is frequently linked to mitigation (figure 8). In contrast, we identified several NbS that incorporate both adaptation and mitigation measures. For example, AG-agroforestry, permaculture-carbon sequestration and permaculture-community-based adaptation were the dominant mitigation-adaptation combinations.

3.2. Synthesis of NbS archetypes

Our study identified two distinct regional archetypes: a development-driven archetype characteristic of low- and middle-income countries (LMICs), and a post-industrial or social benefit archetype, typical of higher- and upper-middle-income countries. The key attributes of the two archetypes are as follows:

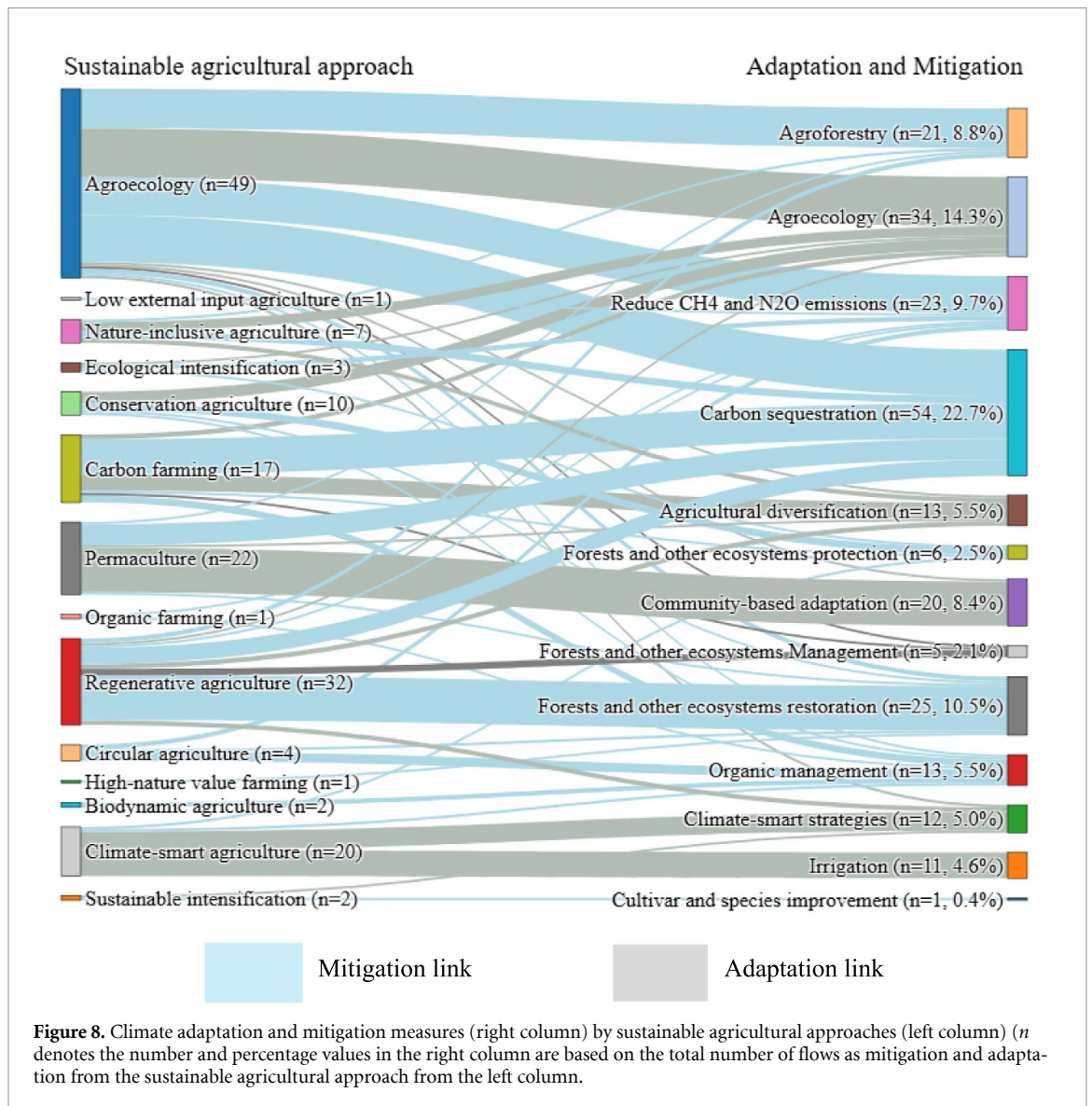
3.2.1. Development-driven archetype

The development-driven archetype characterises efforts to strengthen food security and improve agricultural productivity, with a primary focus on climate adaptation-led pathways (drought/flood adaptation, enhancing soil moisture retention). For example,

agroforestry, community forestry, drought-tolerant varieties, and traditional varieties were reported in LMICs (Barrow 2014, Masseroni et al 2017, Reddy et al 2017, Das and Mallick 2024, Prasad et al 2024). This archetype was primarily found across rural and near-rural areas in South Asia, South-East Asia, Africa, and some Latin American regions. NbS belonging to this archetype were characterised by public funding and planning primarily led by the national government, with coordination and monitoring supported by NGOs. Implementation of NbS was mainly carried out by individuals or households under a top-down governance structure, with limited participation from local governance bodies and minimal cross-sectoral collaboration. NbS under this configuration were mainly linked to supporting (food, fibre) and provisioning (soil formation, nutrient cycling, water retention), as well as some regulatory ES (erosion control). Considering its contribution to sustainable development, NbS of this archetype supports the achievement of SDG targets 2.3 (improve productivity), 2.4 (sustainable food production), and 13.1 (strengthening adaptive capacity).

3.2.2. Post-industrial or social benefit archetype

NbS evidence reported from higher- to upper-middle-income countries focuses on urban agriculture and improving the population's quality of life, biodiversity, and the city's climate resilience, demonstrating social-ecological and economic benefits (Grard et al 2018, De Filippi et al 2019, Sartison and Artmann 2020, Amato and Simonetti 2021). For example, studies on permaculture techniques are most frequently observed in the temperate European region (72% of permaculture), which includes urban gardens (in four studies), and food forestry and



rooftop farming (one study each). NbS identified in this archetype revealed mitigation or integration of mitigation and adaptation aims (reducing emissions and restoring ecosystems, adapting to heat stress). They were mainly found across urban to peri-urban areas of Europe, North America, and some high-income Asia-Pacific countries (China and Australia). Limited evidence of private financiers and multinational governance institutions was found in NbS financing, while implementation roles were led by local or municipal governments. Moreover, this structure featured clear cross-sector collaboration (e.g. among multinational governments, civil society, and academia) with well-defined operational and monitoring mechanisms. Certain prominent ESS related to NbS in this archetype are also worth highlighting. These included regulatory services such as air quality regulation and water management, provisioning services like food provision in peri-urban environments, and cultural services such as social relations. Additionally, these NbS were mainly linked

to SDG targets 15.3 (land restoration) and 2.4 (e.g. sustainable food production in urban agriculture), highlighting global sustainability goals.

3.2.3. Some barriers and scaling pathways

We identified key barriers and enablers to scaling NbS based on the configurations of the aforementioned archetypes and the results of synthesised global evidence. (see supplementary material II, table S1 for characteristics of included articles). Thus, table 1 summarises scaling barriers and approaches for both development-driven and post-industrial NbS archetypes.

4. Discussion

This study provides a systematic synthesis of global evidence on NbS in agriculture aimed at identifying the factors that enable and constrain large-scale implementation. Using narrative configurational

Table 1. Barriers and scaling pathways.

Barriers/scaling pathways	Development-driven archetype	Post-industrial or social benefit archetype
Key scaling barriers	Limited private sector financing	Lack of long-term monitoring data to trace restoration benefits
	Limited local governance authority	Some barriers related to biodiversity versus the maintenance budget
Key scaling pathways	Driven by public-led subsidies/donors and a weak monitoring, reporting and verification (MRV) mechanism	Not enough well-documented metrics for social-ecological benefits
	Some low-cost solutions are not well-documented	Challenges in inclusivity and social justice
	Land ownership rights and access to resources	
	Land tenure reforms	Improve public–private partnerships
	Improve awareness among small-scale farmers	Integrate NbS into local/municipal council development plans
	Delegation of NbS planning, financing and implementation authority to local governance bodies	Promote research into creating more precise NbS social-ecological benefit measurement indicators
	Belended financing option to attract private financiers	Green infrastructure/payment for ecosystem services (PES) funds
	Mostly farmer-led implementation: encourage farmer-to-farmer extension approach	Inclusive and participatory governance approach

synthesis, we identified two income-level archetypes of NbS in agriculture. Archetypes' traits reflect the unique constraints and opportunities for scaling shaped by the social-ecological heterogeneity and governance structure in those countries.

NbS archetype of LMICs was predominantly framed as development-driven and aimed at addressing adaptation to the consequences of climate change while enhancing ecosystem ecological integrity. Moreover, NbS in LMICs are mostly concentrated on ES-supporting (e.g. food production) and food security (e.g. SDG2). For example, investing in agroforestry increases household income, enabling the long-term maintenance of tree cover and reinforcing environmental protection and well-being synergistically (Pinca *et al* 2024). Conversely, agricultural NbS in this archetype were primarily involved by the national government, academics, and individual actors, and were characterised by limited involvement of private financiers (Reddy *et al* 2017, Pendke *et al* 2022, Perron *et al* 2022), suggesting scaling barriers. Our findings revealed limited private sector involvement in NbS interventions that could be highlighted as an emerging area for private financiers to support large-scale applications of NbS in agriculture (Surminski 2013, Petzold *et al* 2023). Scaling agricultural NbS in LMICs seems further limited by the absence of robust MRV mechanisms to capture social, economic and biodiversity-related outcomes. Financial institutions and producer associations emphasised the importance of building financial and market infrastructure to encourage the adoption of NbS in agriculture as a more economically viable solution (Ashton 2022).

The geographic disparity of agricultural NbS studies indicates a strong bias in knowledge production, particularly in LMICs. For example, while NbS evidence for agroecological approaches was mostly found in the Asian region (Legaspi *et al* 2021, Reang *et al* 2024), no evidence was found in Central America. Moreover, LMICs have primarily been reported as locations of knowledge gaps, leading to limited awareness of large-scale NbS adoption (Carvalho *et al* 2022). Thus, some agricultural NbS in those regions are often small, dispersed, and not well-documented, hindering large-scale implementation and wider adoption. Conversely, farmers are key actors in NbS implementation in these regions, enabling farmer-led extension services in developing NbS in LMICs. Local people's knowledge of certain traditional NbS (e.g. agroecological approaches) in LMICs plays an important role in technology transfer and wider adoption, as Indigenous knowledge forms the underlying foundation for practising agricultural NbS in LMICs (Sahana 2025).

In LMICs, the current implementation gap appears to be driven by the lack of NbS governance by local government (Masseroni *et al* 2017, Staccione *et al* 2021, Loveridge *et al* 2023, Sun *et al* 2024, Wang *et al* 2024) and sub-national government (Reddy *et al* 2017, Jha *et al* 2023, Hou *et al* 2024, Panda *et al* 2024, Chenchouni *et al* 2025). When local governance institutions lack sufficient decision-making authority, long-term NbS investment can stall. Weak institutional support and a lack of rule of law, especially in LMICs, can create a challenging environment for investment in agricultural NbS (Löfqvist *et al* 2023). Moreover, secure, legitimate land rights for farmers

in LMICs influence the decision to undertake a large-scale NbS. For example, agroforestry implementation by small-scale farmers has been constrained, as evidenced by weak land tenure rights and insecurity, and failure to translate legal rights by the local authorities (Shennan-Farpón *et al* 2022). While public involvement is crucial for long-term investment as a social safeguard, blended financing encourages the private sector to invest more in agricultural NbS by spreading risk among many actors (e.g. (Löfqvist *et al* 2023).

Agricultural NbS in higher- to upper-middle-income countries were primarily dominated by urban agriculture, which aimed to improve quality of life and climate resilience in cities. For instance, edible cities, which utilise private and public spaces for urban food production, offer multiple environmental, social, and economic benefits (Sartison and Artmann 2020). Nevertheless, we identified some key barriers to scaling NbS in this archetype. Among these, the lack of monitoring data and inadequate metrics limit the realisation of long-term social-ecological benefits, including biodiversity enhancement, thereby hindering investment in NbS in agriculture. The World Bank identifies key barriers to unlocking financing for nature, noting that underpricing, mismanagement, and lack of decision-support tools create uncertainty around natural capital assets, deterring the private sector from these interventions (World Bank 2022). Moreover, NbS in the urban agricultural context are usually characterised by higher costs than conventional farming because of increased maintenance expenses resulting from long-term project cycles (McPherson and Timmer 2002, Evans *et al* 2015) or greater infrastructural investments (Grard *et al* 2018), despite their biodiversity benefits.

In response to these barriers, PES is increasingly recognised as a method to create, improve and safeguard urban ecosystems, encouraging interventions (Richards and Thompson 2019). For example, carbon farming approaches, such as agroforestry (Kaboré *et al* 2024), improved plantations (Kovacs *et al* 2024), and biochar applications (Thers *et al* 2019), are primarily associated with climate-regulatory services, suggesting their applicability to PES. More robust monitoring, reporting, and verification arrangements of ES may enhance further expansion, enhancing the flow of financing into NbS projects in agriculture (Favero and Hinkel 2024). For example, standardised indicators for assessing the NbS contribution to air quality regulation and disease prevention can be based on World Health Organisation guidelines. (World Health Organisation 2025). This ensures that ES are recognised and valued, thereby leveraging investment in NbS in agriculture.

Another challenge we identified is inclusiveness and social justice, mostly faced by agricultural NbS in higher- to upper-middle-income countries. This

challenge has also been emphasised in NbS implementation in urban agricultural contexts (Raymond *et al* 2017, Dorst *et al* 2019). For example, some benefits of agricultural NbS in these regions, such as carbon revenue from agroforestry and tree-based systems, are likely to have inequitable access to benefits (Evans *et al* 2015, Kovacs *et al* 2024). Also, a top-down governance approach impedes community acceptance of NbS in these regions, highlighting the importance of multidisciplinary collaboration and inclusive decision-making (Gasperi *et al* 2016, Artmann *et al* 2020). Local or municipal government institutions emerged to play a key role in NbS interventions in urban and peri-urban areas (e.g. (Gasperi *et al* 2016, Grard *et al* 2018, Artmann *et al* 2020). This suggests that integrating NbS in agriculture into urban governance and infrastructure can foster their wider adoption and scaling up within urban contexts. To further develop agricultural NbS in these areas, we propose more inclusive NbS governance that recognises stakeholders' interests, including those of farmers and the agribusiness sector. Systematic community involvement can foster partnerships, including integrating indigenous knowledge into the design and implementation of NbS in agriculture (McPhearson *et al* 2025).

Conversely, trade-offs between SDG targets and NbS interventions in agriculture are also worth highlighting. For instance, it has been reported that agroforestry can improve carbon sequestration, while dense tree structure reduces crop yield (Bertsch-Hoermann *et al* 2021), highlighting a potential trade-off between the SDG 2 targets (sustainable increase in agricultural production) and 15 (increasing sustainable use of forests). Additionally, some NbS interventions in agriculture, such as organic farming, can have potential trade-offs, resulting in lower crop yields compared to conventional systems (Seufert *et al* 2012).

5. Key policy implications for the successful scaling of NbS in agriculture

In this section, we highlight where policy interventions can maximise the synergistic effect of NbS in agriculture and successful scaling-up. Our findings reveal regional preferences for NbS types, including development-driven archetypes and post-industrial or social benefit. The archetype structure indicates that scaling up NbS in agriculture requires more tailored policy instruments that align with their specific intervention goals. Moreover, developing NbS in LMICs requires robust, implementable agricultural and rural development policies and incentives. For example, providing input supports (e.g. planting materials, machinery), land tenure policies, market access, and price stabilisation

mechanisms are potential policy instruments for development-driven NbS (Phuong *et al* 2024, Reang *et al* 2024). In contrast, upper-middle-income countries face urban sustainability challenges, including reducing emissions and mitigating heat (Panda *et al* 2024). Thus, their NbS strategies focus on urban green infrastructure and enhancing the quality of life, and expansion requires effective urban municipal policies and urban agriculture initiatives (De Filippi *et al* 2019, Kingsley *et al* 2021, Panda *et al* 2024). For example, payments for ES and green municipal financing instruments can be measures applicable to developing post-industrial NbS archetypes.

We found a sparse pattern of actor co-occurrence, indicating a fragmented governance structure for NbS in agriculture. This may reflect strong disconnections among actors in NbS interventions. Thus, we emphasise the importance of institutional policies that enable an inter-institutional coordinating mechanism across local-to-national cross-sector partnerships, recognising the interdependencies among all stakeholders. This dynamic interaction within the NbS social-ecological system is vital, aligning with a country's sustainable development agenda (Ibrahim *et al* 2025). However, there is no one-size-fits-all approach, and such interaction can vary considerably across geopolitical, climatic, and socioeconomic contexts. For example, LMICs with dryland agriculture may prioritise conservation approaches mainly supported by public investment (Klik *et al* 2018), while in upper to middle-income countries, the focus is more on emission-reduction approaches driven by non-governmental agencies.

Additionally, public-private partnerships are crucial for engaging private-sector SMEs and sharing the risks associated with investment in agricultural NbS. Shared governance responsibilities can prompt policymakers to revisit existing NbS governance policies to support successful scaling up. This can enhance private financiers' confidence in investments, encouraging further expansion of NbS in agriculture. Moreover, assistance from governments and NGOs was mainly grant-based for small projects rather than commercial-scale farming (Singh *et al* 2014, Amato and Simonetti 2021, Prasad *et al* 2024). Thus, we suggest integrating NbS into national adaptation planning through vertical integration, as this creates strategic linkages between national and sub-national levels, ensuring that local authorities play a role in advancing adaptation processes. Similarly, embedding NbS into regional development policies enhances governance capacity to achieve systemic, localised, and inclusive NbS (Hölscher *et al* 2023). This can be achieved by incorporating NbS policies into urban planning, agriculture, and financing frameworks.

We emphasise that the ES associated with NbS in agriculture can serve as evidence-based indicators to value ecosystem benefits. For example, NbS outcomes, such as carbon sequestration, can inform policies that promote payment for ES (PES), including targeting of financing sources and desired payment levels through conservation auctions or bidding processes. PES can be used in performance-based blended financing approaches, enabling the several parties involved in NbS to assess investment and outcomes.

NbS and the associated SDG targets can inform the formulation of agricultural investment policies. For example, low-income nations that are primarily aiming to achieve SDG 1 (end of poverty) and SDG 2 (food security and doubling agricultural productivity) can realign agricultural policies by incorporating NbS (Artmann *et al* 2020, Gosnell *et al* 2020, Kingsley *et al* 2021, Prasad *et al* 2024). Our study found synergistic climate benefits of NbS, which align with both mitigation and adaptation in agriculture (Newaj *et al* 2017, Budiman *et al* 2020, Shennan-Farpón *et al* 2022). Thus, decision-makers may tailor NbS interventions for regional development while aligning with local climate policies (Barrow 2014, Neog *et al* 2016, Legaspi *et al* 2021).

6. Conclusions

This study systematically reviews and synthesises 171 articles of global evidence on NbS in agriculture, focusing on factors that hinder their large-scale implementation despite their proven social-ecological benefits. Our typology analysis is based on sustainable agricultural approaches as outlined by the IUCN. A systematic analysis identified 44 distinct NbS practices, which are unevenly distributed geographically. Our findings provide a clearer understanding of NbS preferences across diverse communities. This highlights the importance of context-specific policies to support sustainable farming, rather than relying on a one-size-fits-all approach. Our study identifies two distinct regional archetypes: development-driven archetypes, which focus on LMICs, and post-industrial or social-benefit archetypes, which emphasise urban greening, quality-of-life improvements, and urban biodiversity in higher- to upper-middle-income countries. These findings indicate how governance structure shapes the design and implementation of NbS in sustainable agriculture, and recognising these archetypes suggests different scaling strategies.

Our findings suggest a strong disconnect among actors, hindering the use of NbS in large-scale implementation. The results reveal that NbS in agriculture is primarily publicly funded and academic-led, with limited participation by private-sector financiers.

Moreover, results on ES, SDG targets, and climate co-benefits offer insights into NbS interventions that deliver stronger ecosystem benefits and enhance human well-being. Our findings suggest that the involvement of farmers, policymakers, private-sector financiers, and local civil society is vital to the successful implementation of large-scale NbS in agriculture.

We suggest that the implementation of specific NbS in agriculture should be based on careful consultation with local communities, followed by continuous impact assessment and monitoring. Further research should focus on addressing challenges posed by the complexities of NbS in agriculture across diverse social-ecological contexts. The assessment framework used in this study revealed that scaling pathways of NbS in agriculture can be successfully implemented. Revitalising the cross-sector governance mechanism and localised policy instruments can uphold effective NbS scaling in agriculture.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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