

Article

Mapping the Future of Nature-Based Solutions in Sustainable Agriculture: A Structural Topic Modeling and Socio-Ecological Scenario Analysis

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Abstract

Nature-based solutions (NbS) are increasingly recognized as important strategies for advancing agricultural sustainability and supporting the United Nations Sustainable Development Goals (SDGs). Much research has highlighted the biophysical potential of NbS; however, the literature remains fragmented regarding their socio-economic and governance implications. This study synthesizes existing research, identifies major knowledge structures, and develops a forward-looking research agenda. We analyzed 1198 academic articles using Structural Topic Modeling (STM) to identify ten latent topics. These topics were subsequently mapped onto the adapted Agro-Ecotopia model based on two dimensions: Ecosystem State & Control and Governance Logic & Goal Alignment. This approach established an Agro-NbS analytical framework and identified four exploratory scenarios: Green Regulation, Engineered Ecotopia, Vulnerable Wilderness, and Grassroots Resilience. These scenarios characterize diverse pathways of agricultural NbS development, highlighting potential spatial trade-offs and emerging system vulnerabilities associated with social equity. Furthermore, this study extends traditional biophysical assessments by emphasizing the importance of polycentric governance and Traditional Ecological Knowledge (TEK) in addressing complex climate challenges. The findings contribute to the understanding of agricultural Socio-Ecological Systems (SESs) and provide insights for policymakers seeking to promote a more equitable transition toward sustainable agriculture.

Keywords: nature-based solutions; sustainable agriculture; structural topic modeling; socio-ecological systems; scenario foresight; just transition



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1. Introduction

Nature-based solutions (NbS) represent an emerging strategy for ecological intervention, standing as a strategic priority for global climate governance and the achievement of the UN Sustainable Development Goals (SDGs) [1,2]. NbS will help reduce global greenhouse gas emissions and protect food security (SDG 2) by 2030 [3,4]. Worsening environmental degradation and the vulnerability of resource-intensive traditional farming are forcing governments and practitioners to adopt ecosystem-based alternatives [5,6]. Conceptually, NbS include actions to protect, manage, and restore ecosystems, solving social problems while improving human well-being and protecting biodiversity [7]. This

approach improves system resilience and ecological functions, driving innovations in agriculture such as agroforestry and soil carbon storage [8,9]. Additionally, applying NbS in river basins helps control floods and reduce agricultural pollution [10,11]. While substantial research highlights the physical potential of NbS, we need to review these studies to identify emerging social and ecological trends for sustainable transitions [12,13].

Recent studies have investigated various dimensions of NbS. For example, many scholars highlight the ecological benefits of large-scale afforestation and wetland restoration [4,14]. Others focus on technical challenges, such as measuring ecosystem services accurately [15]. However, current studies mostly focus on local physical data and ecological engineering [16]. Therefore, researchers have not fully studied how NbS affect rural societies, leaving a comprehensive understanding of their future trajectories within complex Socio-Ecological Systems (SESs) under extreme climate change unexplored [17].

Considerable research examines the role of NbS across agricultural areas, including soil remediation [18], urban farming [19], biodiversity conservation [15], and disaster risk reduction [12]. NbS improve resource use efficiency, adaptability, and overall agricultural sustainability [2,20]. However, large-scale NbS projects can create land-use conflicts, harm traditional livelihoods, and lead to unfair policies. Such unintended consequences directly challenge the principles of a Just Transition. [21,22]. Furthermore, we must answer critical questions regarding the future scalability of NbS and their acceptance among local communities. Thus, it is vital to integrate this fragmented literature, emphasize the socio-ecological characteristics of NbS, and map future research directions. Accordingly, this study answers the following research questions based on a comprehensive text-mining approach:

RQ1: What are the core focus areas and latent topics related to NbS in sustainable agriculture research?

RQ2: What new socio-ecological research questions can shape future scenarios for agricultural NbS?

We examined the progress of NbS by analyzing 1198 articles from the Scopus database, using Structural Topic Modeling (STM) to uncover latent themes in academic discourse. Inspired by the knowledge discovery framework [23], we mapped the topics derived from STM and hierarchical clustering onto an adapted Agro-Ecotopia model [24]. The Agro-Ecotopia model is structured along two complementary dimensions: (1) Ecosystem State & Control, representing the degree to which agricultural ecosystems are regulated or affected by external disturbances (Control vs. Amok), and (2) Governance Logic & Goal Alignment, representing the degree of social coordination and institutional coherence (Conflicted vs. Connected). The interaction between these two dimensions generates four exploratory scenarios that characterize different socio-ecological pathways for agricultural NbS. By integrating these outputs, this study develops the Agro-NbS framework. This framework provides a comprehensive understanding of plausible future scenarios, outlining emerging NbS themes and research questions within complex SESs. Based on this framework, we analyzed three layers of knowledge in each quadrant: existing knowledge (“What do we know?”), implementation features (“Characteristics”), and new research questions (“What do we need to know?”). Ultimately, our findings provide crucial theoretical foresight for policymakers and set new research agendas, including evaluating spatial trade-offs, designing fair payment systems, and testing ecological limits under extreme weather to ensure an equitable transition.

2. Theoretical Framework

Nature-based solutions (NbS) have gained global popularity as key strategies for climate mitigation and agricultural resilience [13]. Since its inception, the NbS con-

cept has demonstrated the potential to significantly transform traditional environmental governance.

NbS have the potential to fundamentally disrupt resource-intensive farming practices. The mechanism of NbS operates across three levels: field, landscape, and macro-policy [12]. Field-level NbS focus on localized physical improvements to help farmers increase soil carbon storage and crop yield [25]. Landscape-level NbS work across ecological borders to reduce risks like floods and pollution, requiring multi-stakeholder collaboration to manage complex ecological flows [26]. The macro-policy level includes national frameworks guiding large-scale afforestation and Payment for Ecosystem Services (PES). While macro-level NbS can achieve large carbon reductions, they are frequently challenged by top-down rules and land-use conflicts [27].

NbS are being rapidly integrated into agricultural domains, transforming traditional frameworks (Table 1). For instance, they promote agricultural diversity to enhance biodiversity [20] and utilize urban green infrastructure to regulate microclimates [28]. However, large-scale NbS can threaten vulnerable rural communities, as unfair spatial planning may lead to “green-grabbing” [29]. Thus, top-down ecological engineering may grow faster than local socio-economic capacities. In contrast, polycentric governance models based on Traditional Ecological Knowledge (TEK) can effectively resolve these equity challenges [30].

Table 1. Application of NbS across various agricultural domains.

S. No.	Field	Application	References
1	Soil Carbon Management	Facilitating carbon sequestration through regenerative practices like no-till and biochar.	[18,27]
2	Agro-biodiversity	Promoting agricultural diversification to support multiple ecosystem services without compromising crop yield.	[15,20]
3	Catchment & Eco-DRR	Utilizing constructed wetlands and riparian buffers for hydro-meteorological risk reduction and flood management.	[10,12]
4	Urban Agroecosystems	Integrating nature-based infrastructure to address urban challenges, including heat-island mitigation and food supply.	[19,28]
5	Climate Policy & Governance	Guiding land-based measures and macro-engineering to mitigate global climate change while evaluating spatial feasibility.	[21,27]

Integrating NbS into agricultural governance improves sustainability by paying for ecosystem services (PES), yet it introduces new system complexities lacking in traditional gray infrastructure [31]. Additionally, prioritizing global carbon removal over local land rights raises profound ethical issues concerning spatial justice [32]. Therefore, integrating NbS with existing structures requires a broad approach where ecologists, policymakers, and local farmers cooperate to ensure fair and effective rules [21].

Because agricultural NbS operate at the profound interdisciplinary nexus of ecological engineering (technology) and socio-economic governance (management), predicting their future trajectories requires a robust heuristic tool. Traditional predictive typologies in the climate literature, such as the IPCC’s Shared Socioeconomic Pathways (SSPs) or Representative Concentration Pathways (RCPs), are highly effective at forecasting macro-economic, demographic, and emissions trends. However, their utility for sub-national or sector-specific analyses remains constrained, as SSPs and RCPs are generally constructed at the global scale with limited spatial resolution and simplified assumptions that may not adequately capture local social, cultural, and institutional heterogeneities [33,34]. This standardized scenario framework has been criticized for its shortcomings in representing

local transitions, uncertainty relevant to adaptation, and context-specific barriers such as stakeholder conflicts and community-level acceptance [2,35].

To address this gap, we adapted the scenario-building logic from Gartner [24] to create the Agro-Ecotopia model (Table 2). Although this framework was originally conceptualized for technological foresight, its underlying logic can be extended to agroecological research. From a Socio-Ecological Systems (SESs) perspective, human and natural systems are intricately linked and co-evolve through long-term adaptive dynamics [36–38]. The implementation of NbS is governed by this duality, as it is driven by the continuous interplay between non-human biophysical drivers and human institutional responses [39]. To capture these converging forces, our SESs-based model introduces two specific dimensions. The first is Governance Logic & Goal Alignment (Society: Conflicted vs. Connected), representing the social dimension. The second is Ecosystem State & Control (Technology/Nature: In Control vs. Amok), representing the technological and biophysical dimension.

Table 2. The Agro-Ecotopia model: Four plausible scenarios for NbS in sustainable agriculture.

		Governance Logic & Goal Alignment (Society)	
		Conflicted	Connected
		(Ecological mandates clash with local livelihoods)	(Aligned conservation goals and multi-stakeholder collaboration)
Ecosystem State & Control (Technology/ Nature)	Control (Interventions are highly engineered and top-down)	Scenario 1: Green Regulation “Macro-engineering”	Scenario 2: Engineered Ecotopia “Agro-harmony”
	Amok (Extreme climate shocks overwhelm systems)	Scenario 3: Vulnerable Wilderness “Climate Cascades”	Scenario 4: Grassroots Resilience “Community Survival”

This matrix yields four exploratory scenarios that are designed to be heuristic rather than strictly predictive, consistent with methodological approaches widely applied in place-based SESs research [40]. In this framework, the four scenarios represent interpretative pathways derived from the intersection of the two dimensions rather than deterministic predictions of future states.

Scenario 1, termed “Green Regulation” (Control–Conflicted), represents a pathway where ecosystem conditions are highly controlled through technological and ecological interventions, while governance objectives remain contested due to potential tensions between large-scale environmental goals and local livelihood priorities.

Scenario 2, termed “Engineered Ecotopia” (Control–Connected), describes a pathway where intensive ecological management and technological integration are aligned with broader social objectives, enabling coordinated relationships between human activities and ecosystem functions.

Scenario 3, termed “Vulnerable Wilderness” (Amok–Conflicted), represents a pathway characterized by increasing ecological uncertainty and climate-related disturbances, where environmental pressures exceed governance capacities and generate conflicts over resource allocation.

Scenario 4, termed “Grassroots Resilience” (Amok–Connected), describes a pathway in which communities respond to ecological uncertainty through local knowledge, social networks, and collaborative governance, reflecting the adaptive principles of nature-based solutions that integrate ecosystem protection, sustainable management, and human well-being [41].

Together, these four scenarios provide a heuristic framework for interpreting alternative socio-ecological configurations, where resilience is understood as the capacity of a system to absorb disturbance and reorganize while undergoing change [36,42].

3. Methodology and Data Analysis

3.1. Data Collection and Filtering

We utilized the Scopus database to retrieve studies regarding nature-based solutions (NbS) in sustainable agriculture, as this database comprehensively covers environmental and agricultural sciences [43] and offers strong data extraction tools [44]. We employed a single-database approach to prevent duplicate records and human errors [45].

We searched titles, abstracts, and keywords by combining core NbS terms (“nature-based solution*”) with farming keywords (e.g., agricultur*, farm*, agroforest*), yielding 1523 potential documents. To ensure high-quality and valid text analysis, we excluded non-English papers and limited the results to full “Articles” and “Reviews”. Following this filtration, we established a final dataset of 1198 articles (Figure 1).

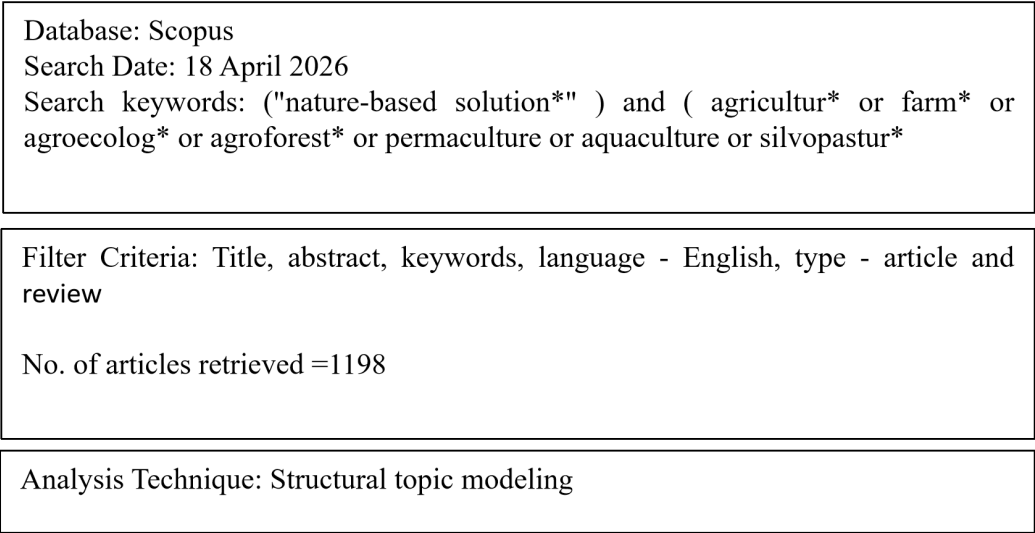


Figure 1. Data retrieval and filtration process for NbS literature.

We analyzed the textual data of these articles in two phases. First, we applied Structural Topic Modeling (STM) to uncover latent topics across all 1198 articles. Second, we conducted an in-depth literature review to identify NbS implementation characteristics and formulate new research questions. The articles included in our final review had to (1) be published in peer-reviewed journals, (2) focus clearly on applying NbS in farming systems, and (3) discuss ecological benefits or socio-economic challenges.

3.2. Descriptive Analysis

Our analysis demonstrates robust growth in NbS agricultural research (Figure 2). The publication volume grew from 39 papers in 2020 to 343 in 2025, indicating a strong scientific consensus on the importance of ecosystem-based farming.

3.3. Structural Topic Modeling

We utilized STM to mine the text of agricultural NbS papers and discover latent topics [46]. Unlike traditional Latent Dirichlet Allocation (LDA), STM provides a flexible framework that allows document-level metadata to be incorporated as covariates for topic prevalence or content estimation [47]. In this study, STM was applied to textual information extracted from article titles, keywords, and abstracts, without incorporating additional

document-level metadata as covariates. The analysis therefore focused on identifying latent thematic patterns emerging from the textual corpus of NbS research.

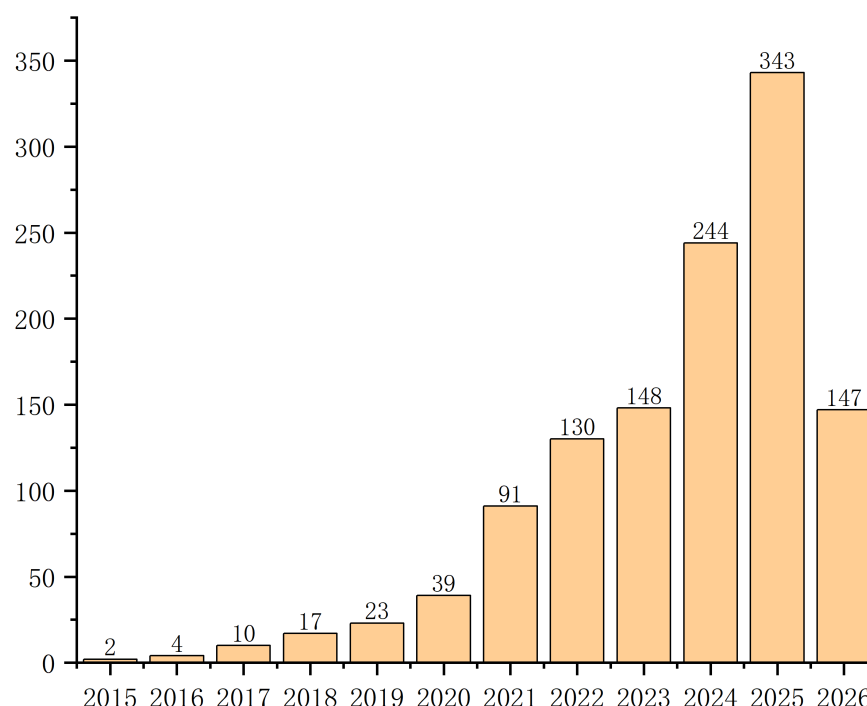


Figure 2. Annual number of publications on nature-based solutions in sustainable agriculture from 2015 to 2026. Note: The 2026 data are partial and include only publications available up to the date of data retrieval.

We cleaned and preprocessed the textual corpus in RStudio prior to model execution. The STM corpus was constructed from article titles, author keywords, and abstracts. The collected text fields were standardized by converting all words to lowercase, removing punctuation and redundant spaces, and filtering standard stop words as well as common terms lacking substantive meaning. These preprocessing steps were applied consistently across all documents before STM estimation.

To identify the optimal number of topics (K), we tested several values using the *searchK* function [48]. The curves for held-out likelihood and semantic coherence balanced best at $K = 10$ (Figure 3); thus, we selected 10 topics. We also evaluated model quality using semantic coherence and exclusivity [49]. Semantic coherence measures how often core words co-occur within a topic, while exclusivity checks their uniqueness compared to other topics. The average exclusivity scores ranged from 8.883 to 9.321, and the semantic coherence scores ranged from -54.569 to -34.549 (Table 3). These metrics confirm that the topics possess distinct features without excessive overlap.

We extracted the top 10 core words for each topic to understand their meanings. We used Highest Probability and FREX scores to find these words. As Kuhn [50] observes, the FREX (Frequency and Exclusivity) algorithm identifies distinctive topic words by computing the harmonic mean of a term's corpus-wide frequency and its exclusivity to a given topic. We utilized these core words to assign each topic a broad academic label.

For example, Topic 1 words focus on agronomy and soil. They include “technosol,” “amend,” “soil,” “salin,” and “biochar.” Based on these words, we labeled it “Technosol Remediation.” Similarly, Topic 4 words focus on carbon. They include “greenhous,” “ghg,” “emiss,” and “account.” This describes agricultural carbon tracking. So, we labeled it “Agricultural GHG Accounting.” We used this logical method to name all 10 NbS topics.

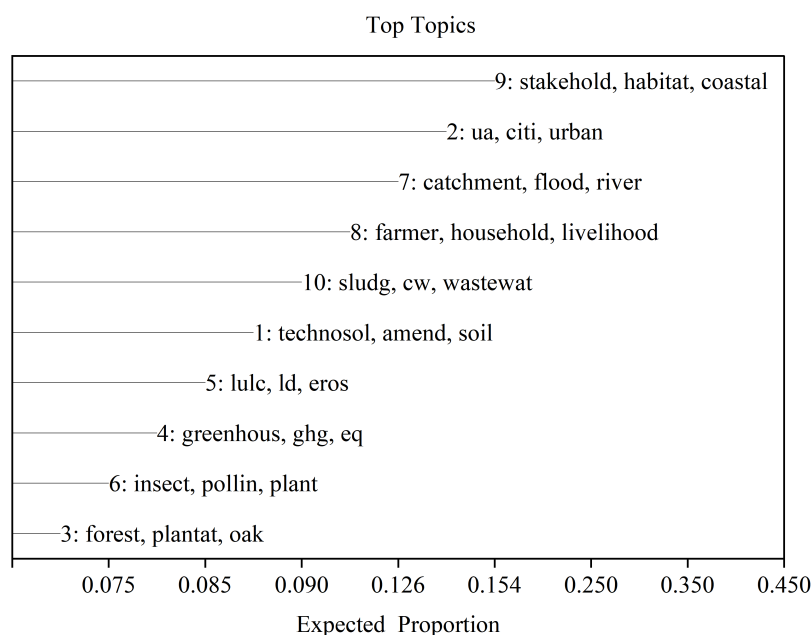


Figure 3. Extracted topic labels and proportions.

Table 3. Extracted latent topics and evaluation metrics from STM.

S. No.	Topic Labels	Highest Prob ($n = 10$)	FREX ($n = 10$)	Coherence	Exclusivity
1	Technosol Remediation	soil, organ, crop, carbon, fertil, plant, salin, amend, biochar, nutrient	technosol, amend, soil, salin, earthworm, soc, tillag, fertil, straw, biochar	−47.013	9.059
2	Urban Agroecology	urban, green, citi, sustain, food, climat, heat, space, peri, infrastructur	ua, citi, urban, green, peri, infrastruct, heat, air, space, food	−34.549	8.883
3	Silviculture & Afforestation	forest, carbon, tree, land, agroforest, restor, climat, plant, stand, divers	forest, plantat, oak, tree, stand, silvicultur, biomass, divers, conifer, carbon	−39.488	9.321
4	Agricultural GHG Accounting	carbon, climat, emiss, sequestr, soil, forest, footprint, mitig, account, eq	greenhous, ghg, emiss, sequestr, climat, carbon, footprint, mitig, account, eq	−36.580	9.176
5	Land Degradation & Erosion	land, use, change, climat, risk, adapt, water, plant, food, sustain	lulc, ld, eros, land, use, change, soil, climat, risk, adapt	−37.950	9.125
6	Agro-biodiversity	plant, crop, climat, pollin, food, risk, adapt, water, soil, land	insect, pollin, plant, crop, weed, pest, divers, resili, climat, food	−49.512	9.103
7	Catchment Flood Mitigation	water, flood, risk, river, catchment, reservoir, adapt, climat, plant, food	catchment, flood, river, risk, reservoir, water, base, model, adapt, climat	−39.734	9.000
8	Smallholder Adaptation	farmer, climat, agroforestri, livelihood, household, land, adapt, risk, water, plant	farmer, household, livelihood, adapt, agroforestri, indigenous, local, knowledg, climat, land	−45.563	8.905
9	Multi-stakeholder Governance	ecosystem, restor, servic, conserv, coastal, habitat, stakehold, adapt, risk, climat	stakehold, habitat, coastal, ecosystem, servic, restor, conserv, adapt, risk, climat	−37.318	9.114
10	Wetland Eco-purification	water, treatment, wetland, wastewat, remov, pollut, plant, adapt, risk, climat	sludg, cw, wastewat, treatment, wetland, remov, pollut, water, plant, adapt	−54.569	9.106

Note: Semantic coherence measures the semantic consistency of words within a single topic; values closer to zero represent better, more interpretable topics. Exclusivity quantifies how distinctive a topic's vocabulary is relative to all other topics; higher numerical values indicate stronger topic separation. Highest Probability (Highest Prob) and FREX are standard term ranking metrics without fixed optimal thresholds.

We calculated a Pearson correlation matrix to test whether our topic results were independent (Figure 4). Statistical rules state that a score above 0.7 means a strong correlation [49]. In our study, all correlation scores were very low, between -0.18 and -0.03 . This weak link proves that the topics are distinct. They do not overlap [51]. This shows that our topic model is accurate and reliable.

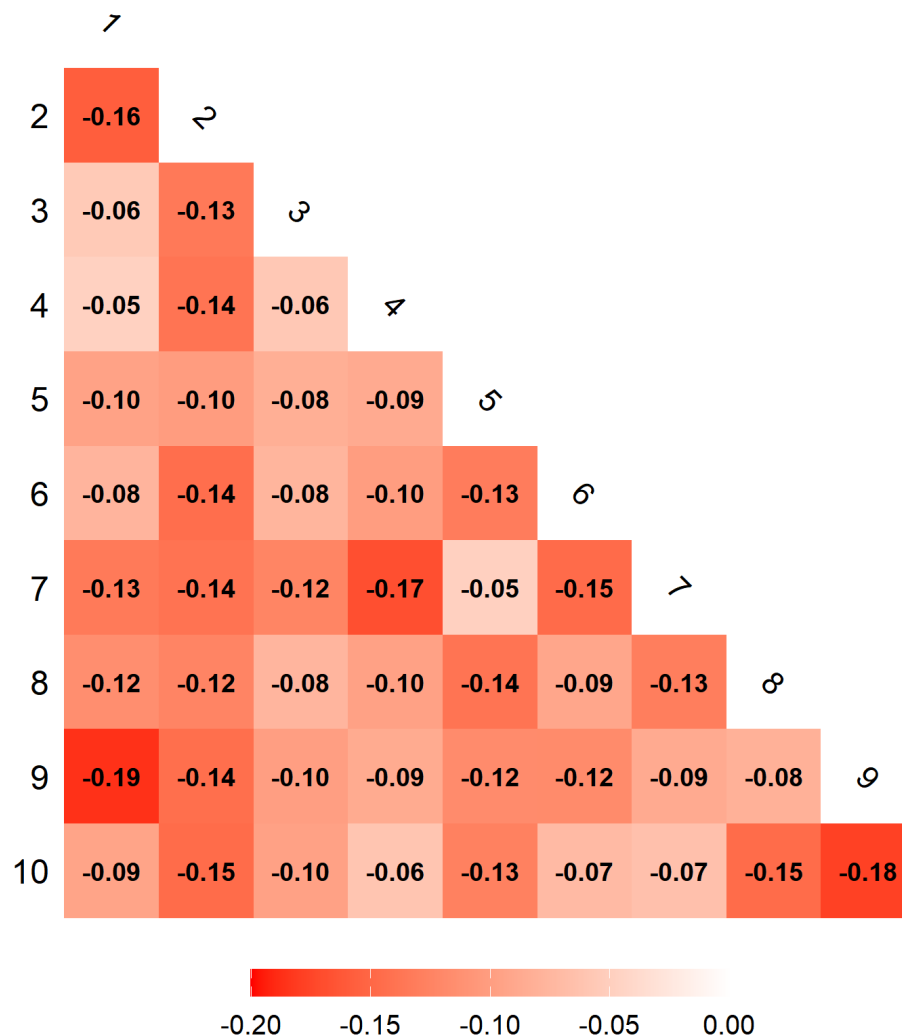


Figure 4. Pearson correlation matrix of the extracted latent topics. The correlation coefficients range from -0.18 to -0.03 , indicating weak negative associations among topics and suggesting that the identified topics capture relatively distinct thematic dimensions.

We plotted a histogram of Maximum A Posteriori (MAP) estimates. This shows how topics are spread across all papers (Figure 5). The graph illustrates that the document proportions for all 10 topics are heavily right-skewed, clustering densely around the 0.0 threshold. This distribution pattern signifies that the vast majority of articles exhibit strong thematic concentration, typically loading heavily onto merely one or two latent topics. From a methodological perspective, such a highly polarized distribution robustly confirms that STM effectively mitigates the risks of semantic overlap and multicollinearity among topics. Consequently, it guarantees that the corpus is parsed into mutually independent and highly distinguishable conceptual categories. Also, we created a hierarchical clustering dendrogram based on semantic distance (Figure 6). This groups the 10 topics into clusters. It reveals the deep structure of sustainable agriculture research [52].

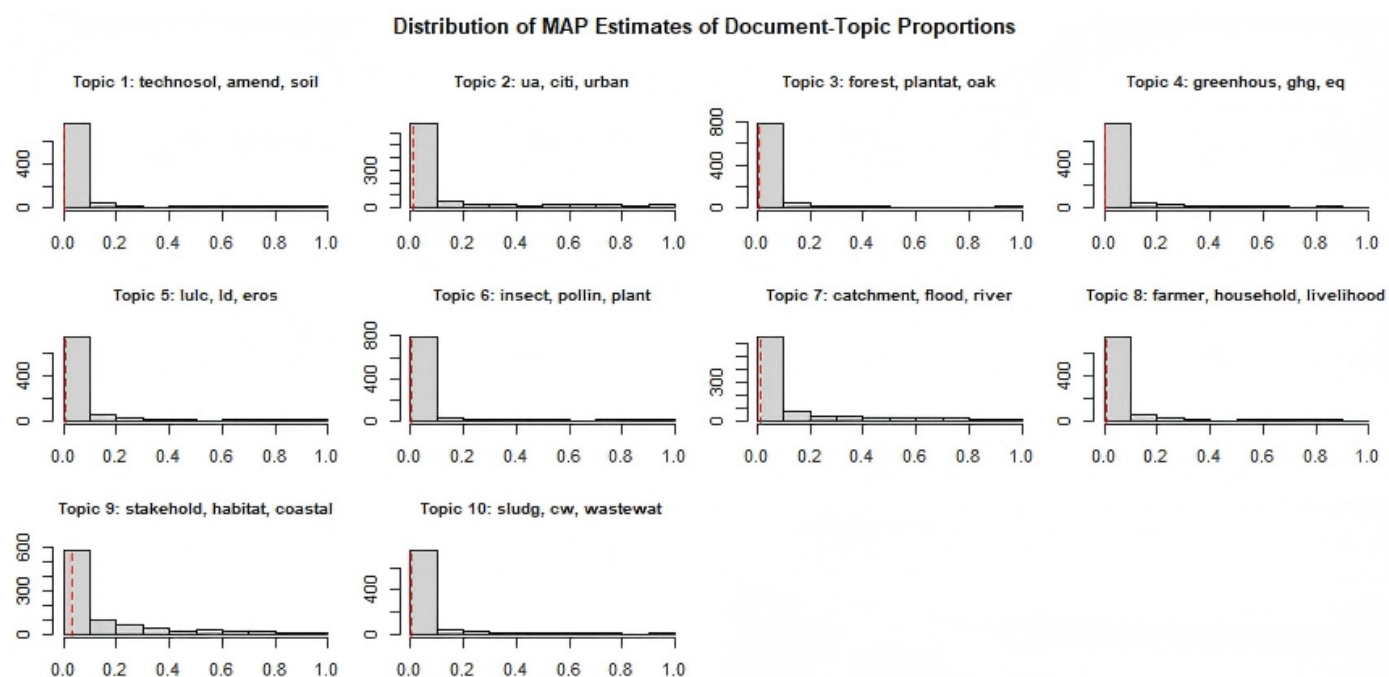


Figure 5. Histogram of Maximum A Posteriori (MAP) estimates for topic proportions. The x-axis represents the proportion of documents associated with each topic, and the y-axis represents the frequency of MAP estimates. The concentration near zero indicates that most topics have relatively low prevalence across the document corpus.

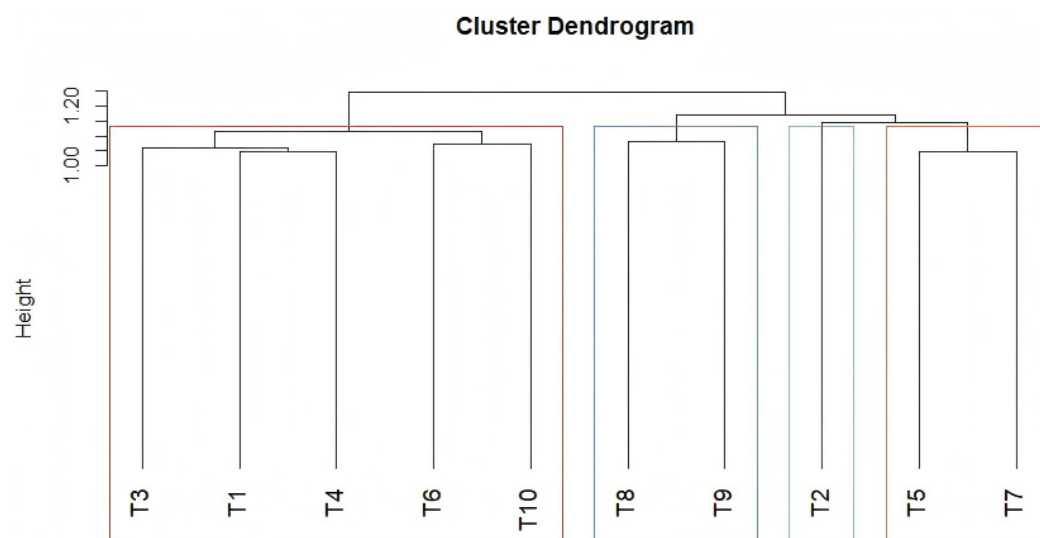


Figure 6. Hierarchical clustering dendrogram of the 10 latent topics.

Finally, we mapped these four data-driven clusters onto the Agro-Ecotopia quadrants (Table 4). To ensure transparency and objectivity, we followed a systematic analytical procedure for this mapping process. The topic distance matrix was calculated based on topic-level semantic similarity, and hierarchical clustering was conducted using Ward's minimum variance method. The resulting dendrogram was then cut into four clusters corresponding to the four analytical scenarios of the Agro-NbS framework.

The mapping process was based on three complementary criteria: (1) the semantic focus of the core keywords; (2) the semantic distances derived from hierarchical clustering; and (3) theoretical triangulation using Socio-Ecological Systems (SESs) theory.

Table 4. Mapping of STM-derived topic clusters onto the Agro-Ecotopia quadrants and corresponding scenarios.

		Governance Logic & Goal Alignment	
		Conflicted	Connected
Ecosystem State & Control	Control	Scenario 1: Green Regulation Topic 1: Technosol Remediation; Topic 3: Silviculture & Afforestation; Topic 4: Agricultural GHG Accounting; Topic 6: Agro-biodiversity; Topic 10: Wetland Eco-purification.	Scenario 2: Engineered Ecotopia Topic 2: Urban Agroecology.
	Amok	Scenario 3: Vulnerable Wilderness Topic 5: Land Degradation & Erosion; Topic 7: Catchment Flood Mitigation.	Scenario 4: Grassroots Resilience Topic 8: Smallholder Adaptation; Topic 9: Multi-stakeholder Governance.

Applying these criteria explains the quadrant assignments. For example, the algorithm grouped Topics 1, 3, 4, 6, and 10 into the largest cluster. Their core keywords highlight technological interventions, ecological restoration, and standardized environmental management approaches (e.g., “GHG” and “technosol”). Therefore, this cluster was mapped to the “Control–Conflicted” quadrant, corresponding to Scenario 1: Green Regulation.

Notably, Topic 2 (Urban Agroecology) formed a distinct semantic cluster due to its unique thematic focus compared with the other topics. This clustering reflects differences in research emphasis, particularly regarding urban environments, artificial infrastructures, and localized ecosystem management, rather than indicating that urban agroecosystems are disconnected from broader agricultural systems. Urban agroecosystems remain embedded within wider socio-ecological networks through food systems, resource flows, knowledge exchange, and climate adaptation processes. Consequently, Topic 2 was mapped to the “Control–Connected” quadrant, corresponding to Scenario 2: Engineered Ecotopia.

The mapping results were independently reviewed by two researchers, and any differences were resolved through discussion to minimize subjective interpretation. The final mapping achieved an inter-rater agreement exceeding 90%.

Structural Topic Modeling (STM) was applied to the corpus of 1198 articles, and 10 latent topics were identified using the searchK function. To further explore the structural relationships among these topics, hierarchical clustering was conducted based on topic-level semantic distances. A topic distance matrix was calculated, and Ward’s minimum variance method was applied to generate a dendrogram (Figure 6). The dendrogram was subsequently split into four clusters, representing four data-driven thematic groups.

The first cluster represents the largest group, including Topics 1, 3, 4, 6, and 10. These topics share a strong emphasis on macro-scale ecological interventions, technological solutions, and standardized environmental management. The second cluster consists of Topics 8 and 9, which focus on social resilience, stakeholder participation, and grassroots governance. The third cluster includes Topics 5 and 7, representing ecological vulnerability, land degradation, and disaster-related responses. In contrast, Topic 2 (Urban Agroecology) forms an independent cluster due to its distinct thematic profile, characterized by urban environments, artificial infrastructures, and localized ecosystem management.

Importantly, the independent clustering of Topic 2 does not indicate that urban agroecosystems operate separately from rural agricultural systems. Rather, it reflects a distinctive research focus within the nature-based solutions (NbS) literature. Urban agroecosystems remain embedded within broader socio-ecological networks through food systems, resource flows, regional climate interactions, and sustainability transitions. Based on these four data-driven clusters, we subsequently mapped the topic groups onto the adapted Agro-Ecotopia framework to conceptualize four potential socio-ecological scenarios for agricultural NbS (Table 4).

To ensure transparency and objectivity, the scenario mapping followed three complementary criteria: (1) the semantic focus of core keywords; (2) semantic distances derived from hierarchical clustering; and (3) theoretical triangulation using Socio-Ecological Systems (SESs) theory. Therefore, the quadrant assignments represent an integration of quantitative topic relationships and theoretical interpretation rather than subjective categorization.

3.4. Scenario 1: Green Regulation (Control–Conflicted)

In this scenario, ecological systems remain highly regulated, while governance objectives experience potential conflicts between large-scale environmental targets and local livelihood priorities. This quadrant corresponds to the largest topic cluster, including Technosol Construction (T1), Silviculture and Afforestation (T3), Agricultural GHG Accounting (T4), Agro-biodiversity Conservation (T6), and Wetland Eco-purification (T10).

NbS function primarily as a standardized ecological management and mitigation approach, enabling large-scale interventions in agricultural landscapes. For example, agricultural carbon accounting systems support emission reduction strategies, while constructed wetlands improve pollution interception and ecosystem purification capacity [53,54]. However, the implementation of large-scale ecological engineering may introduce governance tensions. Strict land-use regulations and standardized management practices can constrain local decision-making and reduce flexibility for smallholder farmers, challenging principles of social equity and a Just Transition [55].

3.5. Scenario 2: Engineered Ecotopia (Control–Connected)

This scenario represents a highly regulated but socially coordinated pathway, where governance objectives and ecological management strategies are relatively aligned. It is represented by Topic 2 (Urban Agroecology), which emerged as an independent semantic cluster due to its distinctive research emphasis on urban ecological integration, artificial infrastructures, and controlled production environments. This clustering reflects a difference in research focus rather than a separation of urban agroecosystems from broader agricultural systems.

Urban agroecosystems demonstrate how NbS can be incorporated into densely populated areas through green infrastructure, urban farming systems, and ecological design. Rather than representing an isolated urban pathway, urban NbS are embedded within broader rural–urban food systems through material flows, knowledge exchange, resource circulation, and regional sustainability transitions. Through intensive management and technological integration, this pathway enhances urban food resilience, mitigates environmental pressures such as heat-island effects, and improves local ecosystem services [56].

Therefore, Scenario 2 reflects a form of “engineered ecotopia” in which human-designed ecological systems achieve strong coordination between technological control, urban development, and sustainability objectives.

3.6. Scenario 3: Vulnerable Wilderness (Amok–Conflicted)

This scenario represents a high-risk pathway in which ecological uncertainty increases while governance responses remain fragmented. It is characterized by two hazard-oriented topics: Land Degradation and Erosion (T5) and Catchment Flood Mitigation (T7).

Under increasing climate pressures and ecological degradation, agricultural systems face risks that exceed existing management capacities. In this context, NbS primarily function as an adaptive buffering mechanism by restoring ecological functions, improving water retention, and reducing disaster vulnerability. For example, flood-retention landscapes contribute to Ecosystem-based Disaster Risk Reduction (Eco-DRR) by enhancing hydrological regulation and landscape resilience [57].

However, the expansion of ecological buffering measures may create competing demands for limited agricultural land resources. Balancing ecosystem protection and agricultural production therefore remains a major governance challenge under this scenario.

3.7. Scenario 4: Grassroots Resilience (Amok–Connected)

This scenario describes conditions where ecological uncertainty remains high, but governance responses are strengthened through local participation and social connectivity. It includes two topics: Smallholder Livelihood Resilience (T8) and Multi-stakeholder Collaborative Governance (T9).

Unlike large-scale technological interventions, this pathway emphasizes the adaptive capacity of communities and the importance of social capital. Under climate uncertainty, local actors develop livelihood buffering strategies through Traditional Ecological Knowledge (TEK), collective action, and informal governance networks. These locally embedded practices enhance agricultural resilience by mobilizing contextual knowledge and strengthening adaptive capacity [58].

Overall, this scenario highlights the importance of combining ecological adaptation with participatory governance mechanisms to achieve resilient agricultural NbS pathways.

4. Discussion

The comprehensive analysis of 1198 articles elucidates the evolving trajectories of nature-based solutions (NbS) in sustainable agriculture. The Structural Topic Modeling (STM) analysis successfully extracted 10 distinct macroscopic topics, ranging from Technosol Remediation to Agro-biodiversity Conservation and GHG Accounting. To construct a forward-looking roadmap, these 10 topics were mapped onto four futuristic scenarios by synthesizing the Agro-Ecotopia model [24] with a knowledge discovery framework [23], culminating in the development of the Agro-NbS framework (Figure 7). Furthermore, the STM-derived topics were interpreted as knowledge structures rather than direct evaluations of system performance. By combining topic patterns with a qualitative literature synthesis, we identified major knowledge gaps and translated them into potential methodological directions, including quantitative assessment, participatory governance analysis, and integrated socio-ecological modeling. Drawing upon the knowledge discovery framework, we systematically dissected the epistemic landscape of NbS across each quadrant into three logical layers. First, the existing literature was evaluated and synthesized under “What do we know?” Second, the intrinsic implementation features of NbS under each scenario were distilled as “Characteristics of NbS.” Third, the identified research gaps were translated into targeted future inquiries under “What do we need to know?”, offering a holistic blueprint of the emerging socio-ecological scenarios.

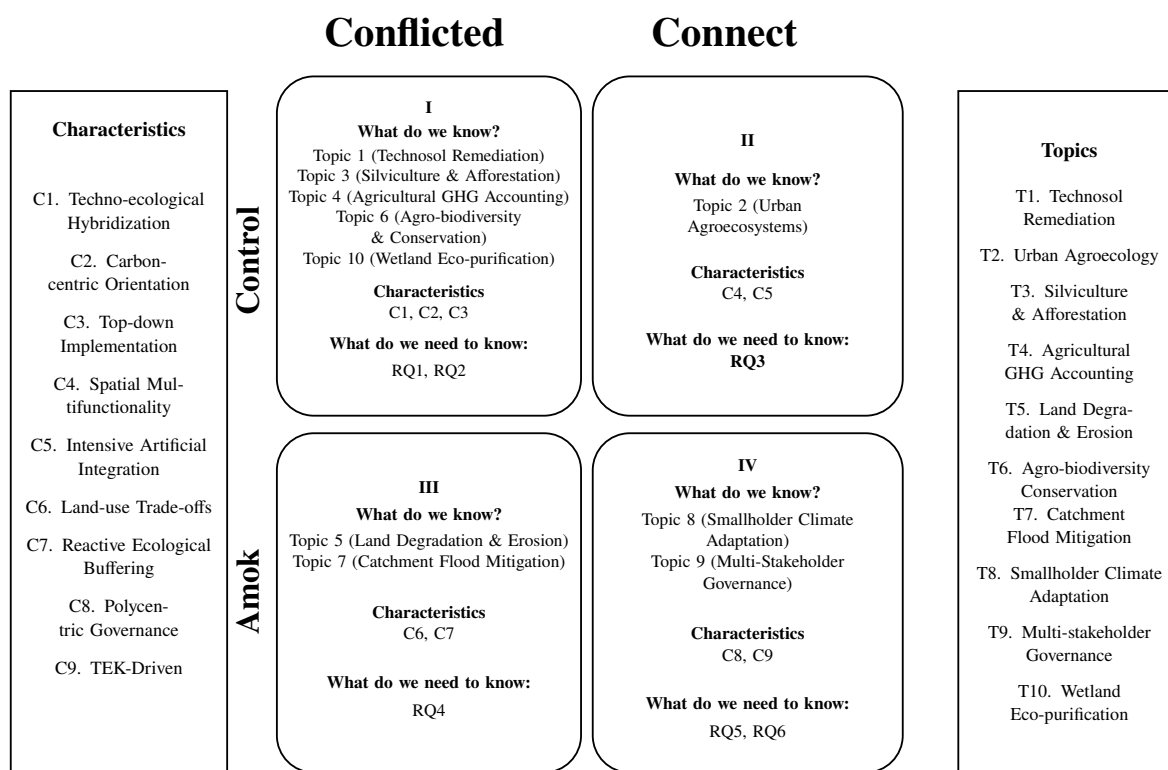


Figure 7. The Agro-NbS framework for sustainable agriculture. C denotes characteristics, T denotes topics, and RQ denotes research questions.

4.1. Quadrant 1: Control–Conflicted

What do we know?

This quadrant explicitly reveals the dominant role of “Techno-ecological Managerialism” in the current global sustainable agricultural transition. Academic research and practices are highly focused on systematically optimizing and precisely quantifying natural processes through engineering strategies [59]. Within this framework, NbS are efficiently positioned as strategic tools to achieve macro-level goals, such as national carbon neutrality [60]. This macro-ecological engineering exhibits immense scaling potential in restoring degraded habitats and enhancing carbon sink capacities, providing a solid practical foundation for fulfilling global climate commitments [61].

Characteristics of NbS

In this scenario, NbS implementation is characterized by highly Techno-ecological Hybridization (C1) and a Carbon-centric Orientation (C2). It heavily relies on hierarchical, Top-down Implementation (C3) as its primary enforcement mechanism. These three elements constitute the structural dependency for scaling NbS under this scenario.

What do we need to know?

The advancement of large-scale NbS projects and their pursuit of singular quantitative targets (e.g., carbon sinks) easily create tension with the complexity of local agroecosystems and smallholder livelihoods [55]. This structural contradiction between “top-down control logic” and “bottom-up adaptive demands” highlights the following macro-issues for a Just Transition:

RQ1: How can multi-dimensional evaluation models be systematically constructed to scientifically weigh the long-term ecological benefits against regional socio-economic costs in large-scale agricultural NbS implementation, avoiding excessive policy focus on singular emission reduction metrics? [59,62]

RQ2: How can an ecological governance framework with both institutional flexibility and social inclusivity (e.g., diversified Payment for Ecosystem Services mechanisms) be designed to synergize macro-environmental goals with the endogenous development rights of local communities? [63]

RQ1 focuses on cross-scalar eco-economic trade-offs. Given that the identified literature emphasizes carbon accounting and large-scale ecological interventions, future research could combine System Dynamics and Life Cycle Assessment (LCA) to quantify the broader ecological and socio-economic consequences of NbS implementation, including potential impacts on regional food systems. RQ2 focuses on institutional inclusivity in environmental governance. Future research can explore how property rights security and model innovation can transform grassroots farmers from passive recipients of ecological regulations into tangible beneficiaries of the green transition.

4.2. Quadrant 2: Control–Connected

What do we know?

This quadrant reveals a synergistic socio-ecological paradigm achieved in highly controlled, de-naturalized environments. Urban agroecosystems represent a differentiated form of agricultural development embedded within broader food systems. Rather than replacing rural agriculture, urban NbS interact with regional production networks, resource flows, and sustainability transitions. They have become “urban experimental spaces” for exploring the systemic fusion of intensive human intervention and natural processes [64]. In closed or semi-closed urban green infrastructure, by circumventing non-linear climate disturbances, NbS can precisely regulate and directionally output ecosystem services, demonstrating a highly coupled system morphology in human-dominated habitats [60].

Characteristics of NbS

In this scenario, NbS shed the extensiveness of traditional agriculture, embodying ultimate Spatial Multifunctionality (C4) and Intensive Artificial Integration (C5).

What do we need to know?

Beneath the facade of the “engineered ecotopia,” dense urban environments pose severe challenges to resource circulation and system integration:

RQ3: In severely space-constrained urban architectural environments, how can the multiple ecosystem service outputs of urban agricultural infrastructure (e.g., vertical farms) be maximized through spatial morphological optimization and technology integration? [65,66]

RQ4: How can the Water–Energy–Food (WEF) nexus within closed/semi-closed urban NbS be optimized to drive resource loops and emission reduction synergies across the entire life cycle of artificial ecosystems? [67]

RQ3 focuses on the physical integration efficiency of NbS within highly intensified spaces. Future research can combine urban morphology and building physics to quantify the comprehensive efficacy of different vegetation canopy and building envelope combinations. RQ4 focuses on the material circulation limits of artificial ecosystems. Future research can conduct detailed Material Flow Analysis based on LCA to explore the integration pathways of urban graywater recovery and organic waste composting technologies.

4.3. Quadrant 3: Amok–Conflicted

What do we know?

When the impacts of climate change breach ecosystem tipping points, the narrative shifts drastically from “proactive ecological construction” to “passive disaster response.” Studies have systematically revealed the destructive cascading effects between extreme hydrological events and soil degradation [68]. Under extreme constraints, NbS extensively

utilize the physical space and hydrological retention functions of ecosystems (e.g., flood-retention wetlands, riparian buffers) to exert the flexible defensive role of Ecosystem-based Disaster Risk Reduction (Eco-DRR) [69,70].

Characteristics of NbS

Against escalating climate risks, NbS profoundly reflect the Land-use Trade-offs (C6) between disaster-prevention ecological spaces and agricultural production lands; their implementation orientation shifts toward Reactive Ecological Buffering (C7).

What do we need to know?

Faced with cascading disaster challenges and spatial competition in NbS implementation, clarifying the adaptive boundaries of natural interventions is a prerequisite for enhancing agricultural resilience:

RQ5: Under the exacerbating risks of soil and water cascading disasters, how can the comprehensive ecological resilience and disaster buffering thresholds of agricultural NbS (e.g., riparian buffers) during extreme climate events be systematically assessed? [71,72]

RQ6: Under hard constraints of land resources, how can “Gray–Green Infrastructure” collaborative planning at the watershed scale optimize the spatial configuration of disaster reduction functions and agricultural production lands? [73]

RQ5 focuses on defining the ecological effectiveness boundaries of Eco-DRR measures. Based on the identified emphasis on disaster mitigation and ecological buffering in the literature, future research could utilize macro-climate and hydrological coupled models from a dynamic stress-testing perspective to explore the response mechanisms of various NbS under multiple meteorological stresses. RQ6 focuses on spatial optimization at the macro-landscape scale. Future research could explore organically combining the reliability of modern hydraulic engineering with the flexibility of natural ecosystems to find the optimal spatial equilibrium among disaster prevention, ecological protection, and agricultural production.

4.4. Quadrant 4: Amok–Connected

What do we know?

Unlike macro-engineering perspectives, this quadrant highlights the foundational supporting role of human social capital in maintaining agricultural operations against high-uncertainty risks. The academic focus is shifting toward bottom-up social collaborative networks [74,75]. The literature indicates that by adapting Traditional Ecological Knowledge (TEK) and building informal mutual-aid networks, vulnerable communities can establish resilient livelihood buffering mechanisms. This spontaneous adaptation practice effectively compensates for the limitations of standardized engineering under localized climate perturbations [76,77].

Characteristics of NbS

Here, NbS implementation transcends traditional hardware engineering, showcasing deep sociological attributes. Its operation heavily relies on decentralized Polycentric Governance (C8), driven by endogenous TEK (C9) as its core methodology.

What do we need to know?

The emphasis on TEK and polycentric governance identified in this thematic cluster suggests the need for participatory and community-based approaches. These perspectives prompt a re-evaluation of technology-dominated climate adaptation frameworks and highlight the importance of integrating local knowledge and stakeholder participation into future NbS research:

RQ7: How can the adaptive mechanisms of TEK be systematically excavated and verified within scientific cognitive systems, effectively mainstreaming them into modern agricultural climate adaptation policy frameworks? [78,79]

RQ8: In marginalized agricultural regions with weak macro-resource allocation, how can institutional and resource barriers to NbS promotion be overcome by building collaborative evolutionary networks across polycentric stakeholders (including local communities, NGOs, and public sectors)? [80]

RQ7 focuses on the co-production of knowledge systems. Future interdisciplinary research can qualitatively and quantitatively assess the stress-resistance performance of traditional agroecological practices (e.g., endemic agroforestry). RQ8 focuses on resource network reconstruction under decentralized conditions. Future research can employ Social Network Analysis (SNA) to dissect the micro-flow pathways of knowledge and technology, exploring innovative inclusive cooperation mechanisms for bottom-up NbS practices [81].

5. Implications

5.1. Theoretical Implication

NbS represent a transformative ecological intervention strategy with vast application potential. By integrating the outputs of Structural Topic Modeling (STM) with the adapted Agro-Ecotopia scenario model [24] and a knowledge discovery framework [23], this study develops the Agro-NbS framework. This framework provides a comprehensive understanding of plausible future scenarios, outlining emerging NbS themes and research questions within complex Socio-Ecological Systems (SESs).

This study is an attempt to synthesize fragmented academic developments and conceptualize future trajectories using scenario-building logic. It advances the academic literature in three primary ways. First, it systematically broadens the epistemic boundaries of NbS by objectively revealing the structural bifurcation between top-down “techno-ecological managerialism” and bottom-up “grassroots collaborative governance.” Second, the study identifies critical research gaps that must be addressed under dynamic climate pressures. For instance, in an extreme scenario where climate runs amok and resource conflicts intensify, rigid technological optimism often fails; instead, social capital and polycentric governance—driven by Traditional Ecological Knowledge (TEK)—become fundamental for system survival [82]. This comprehensive integration of ecological and socio-economic dimensions aligns seamlessly with the UN Sustainable Development Goals (SDGs) [83]. Third, addressing the identified shortcomings regarding spatial trade-offs and epistemic barriers in current NbS implementation, this study pinpoints a promising frontier for methodological evolution: the shift from singular biophysical measurements toward the deep integration of System Dynamics Modeling, Life Cycle Assessment (LCA), and Environmental Sociology [84,85]. This interdisciplinary theoretical extension is poised to not only quantitatively evaluate the hidden costs of macro-ecological engineering on regional food security but also provide the foundational theoretical framework to bridge the epistemic divide between TEK and modern hierarchical governance.

5.2. Practical and Policy Implications

The identified research themes and emerging scenarios offer valuable foresight for policymakers, watershed managers, and agricultural practitioners aiming to achieve the SDGs. To effectively combat climate change, macroscopic policy design must eschew “one-size-fits-all” ecological mandates. When implementing large-scale NbS projects (e.g., afforestation or constructed wetlands), governments must design inclusive Payment for Ecosystem Services (PES) mechanisms to reconcile national carbon neutrality targets with the micro-livelihoods of smallholder farmers [86,87]. Secondly, in agricultural catchments prone to

hydrological disasters, authorities should pivot from singular gray infrastructure towards “gray–green” hybrid solutions, leveraging NbS to enhance Ecosystem-based Disaster Risk Reduction (Eco-DRR) [88]. For urban planners, actively incorporating urban agroecosystems (e.g., vertical farms) as green infrastructure can optimize the local Water–Energy–Food (WEF) nexus while mitigating urban heat islands [89]. Furthermore, international organizations and NGOs should increase investments in “soft infrastructure” within marginalized farming communities, fostering endogenous climate resilience by mainstreaming TEK and cultivating polycentric collaboration networks [90].

5.3. Limitations and Future Research

This study acknowledges certain limitations. First, the STM analysis was performed exclusively on article titles, keywords, and abstracts rather than full texts. While abstracts are highly condensed and widely used for topic modeling, they may not fully capture nuanced socio-economic arguments, methodological details, or governance challenges typically discussed in the body of the paper. This limitation might inadvertently bias the topic distribution toward biophysical or ecological engineering themes. To address this, future research is recommended to employ full-text topic modeling or to conduct a comparative analysis of topic proportions between abstracts and a representative subset of full texts, thereby assessing the consistency of the thematic distribution and cross-validating these findings. Second, the corpus was extracted exclusively from the Scopus database and limited to English-language publications [91]. Although Scopus provides broad interdisciplinary coverage and extensive indexing of environmental and agricultural research, reliance on a single database may inevitably introduce potential coverage bias. Relevant studies indexed in other databases, such as Web of Science, or published in regional languages may not be fully represented in our corpus. Future research could integrate multiple bibliographic databases and multilingual sources to provide a more geographically inclusive understanding of agricultural NbS research. Additionally, the exploratory 2×2 quadrant projection of the Agro-Ecotopia model simplifies the intricate, non-linear dynamic feedback loops characteristic of real-world Socio-Ecological Systems (SESs). Consequently, without empirical grounding, the proposed scenario framework currently remains heuristic and exploratory. Future research could employ ethnographic approaches and participatory action research, working directly with farming communities to assess the applicability of these macro-scenarios in localized contexts [83]. Finally, exploring the integration of macro-ecological–hydrological coupled models and dynamic stress testing into NbS efficacy evaluations—aimed at quantitatively simulating system collapse thresholds and ecological tipping points under cascading extreme disasters—remains a crucial and compelling endeavor for future research [92].

6. Conclusions

This study presents a quantitative review and exploratory scenario analysis of academic research on nature-based solutions (NbS) in sustainable agriculture. By applying Structural Topic Modeling (STM) to 1198 articles retrieved from Scopus, we identified 10 major research topics and organized them into four thematic clusters through hierarchical clustering. These clusters were further interpreted through the Agro-Ecotopia framework to explore plausible socio-ecological pathways for agricultural NbS.

The findings suggest that agricultural NbS research has increasingly expanded beyond purely biophysical assessments by incorporating technological, ecological, socio-economic, and governance dimensions. The four scenarios identified in this study should not be interpreted as deterministic future states; rather, they represent alternative configurations

of ecological conditions, governance approaches, and knowledge structures within inter-connected Socio-Ecological Systems.

The first scenario (Control–Conflicted) highlights a pathway dominated by large-scale technological and ecological interventions, including carbon accounting, technosol applications, afforestation, biodiversity conservation, and constructed wetland systems. While these approaches provide opportunities for ecological restoration and climate mitigation, they may also generate tensions associated with land-use trade-offs, institutional coordination, and stakeholder inclusion.

The second scenario (Control–Connected) represents an urban-integrated pathway centered on Urban Agroecology. The independent semantic clustering of Topic 2 reflects its distinctive research emphasis on artificial environments, urban infrastructures, and localized ecosystem management rather than its separation from broader agricultural systems. This pathway illustrates how intensive ecological design and technological integration may contribute to urban food resilience while remaining connected with wider socio-ecological networks.

The third scenario (Amok–Conflicted) represents a vulnerable pathway characterized by increasing ecological uncertainty, land degradation, and climate-related disturbances. In this context, NbS function primarily as an adaptive buffering mechanism to reduce disaster risks and restore ecosystem functions. However, balancing ecological protection with agricultural production remains an important governance challenge.

The fourth scenario (Amok–Connected) emphasizes grassroots resilience under conditions of ecological uncertainty. It highlights the importance of social capital, Traditional Ecological Knowledge (TEK), and multi-stakeholder governance in strengthening adaptive capacity and supporting locally embedded NbS implementation.

Overall, this study contributes an integrated analytical framework linking STM-based evidence synthesis with socio-ecological scenario development. Although STM identifies patterns within scientific knowledge rather than directly predicting ecological outcomes, combining topic structures with SESs theory provides a systematic approach for interpreting emerging research trajectories and identifying future research priorities. The Agro-NbS framework offers a conceptual basis for examining inclusive governance, adaptive management, and context-sensitive approaches that may support future studies on sustainable agricultural transitions under increasing environmental complexity.

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