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Plant Ecology and Ecosystem-Based Approaches: Challenges and Opportunities for Climate Resilience

Hooman Babanezhad[1]
1. Department of Plant Science, Faculty of Basic Sciences, University of Mazandaran, Babolsar, Iran.

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ABSTRACT

Nature-based solutions (NbS) offer promising strategies to enhance climate resilience by leveraging ecological processes, particularly those driven by plants. This study investigates the integration of plant ecology into ecosystem-based approaches to improve the effectiveness of NbS for climate adaptation. Through a conceptual review of over 60 peer-reviewed studies published between 2015 and 2024, the research highlights the role of plant functional traits and biodiversity in regulating key ecosystem services, including carbon sequestration, hydrological balance, and habitat conservation. Results show that NbS projects incorporating ecological metrics achieved up to 30% higher effectiveness in climate resilience compared to conventional methods. The findings underscore the need to bridge ecological theory with practical frameworks to develop scalable, evidence-based solutions. This integration not only enhances the sustainability of natural resource management but also fosters stronger collaboration between scientific research and environmental policy.

Introduction

Solutions addressing the dual crises of climate change and ecological degradation have become one of the most pressing challenges of our time. Immediate and coordinated efforts are needed—both locally and globally, not only to slow down and halt these environmental threats but also to reverse their impacts [1]. Solutions must tackle the unsustainable use of terrestrial and aquatic ecosystems to create a resilient future in which both people and the natural world can thrive amid ongoing planetary changes [2], [3].

To meet the targets set by major international frameworks—such as the Paris Agreement, which demands rapid climate action, and the Kunming–Montreal Global Biodiversity Framework, which emphasizes the protection and restoration of biodiversity—there is an urgent need for integrated approaches. These twin crises of climate and biodiversity are deeply interconnected and cannot be solved in isolation. A siloed response risks inefficiency, redundancy, or even counterproductive outcomes. Instead, there is a growing consensus that solutions must be holistic, working across ecological, social, and climate related dimensions [4], [5].

Nature-based solutions (NbS) have emerged as a promising and inclusive framework to address this complex web of challenges. NbS refers to a broad spectrum of strategies grounded in ecological principles involving the management, restoration, and sustainable use of natural and managed ecosystems. They aim to deliver tangible benefits for both people and biodiversity while tackling societal challenges such as climate change, food insecurity, water scarcity, and disaster risk. At their core, NbS recognize the reciprocal relationship between people and ecosystems—humans are both stewards of and beneficiaries of the services that ecosystems provide [5], [6], [7].

A key strength of NbS lies in its ability to harmonize human and ecological well-being. They are rooted in actions that enhance ecosystem health and resilience, thereby offering solutions that are not only environmentally sound but also socially inclusive and economically viable. Central to the success of NbS is the role of plants, arguably the most foundational life form in terrestrial ecosystems. Plants influence biogeochemical cycles, regulate greenhouse gas emissions, and mediate the impacts of climate change on ecosystem stability and productivity. As such, plant ecology provides critical insights into how ecosystems function and how their services can be harnessed and sustained over time [4], [6], [8].

Historically, the principles of plant ecology have informed a variety of applied fields such as ecosystem-based management, agroecology, forestry, ecological restoration, and conservation biology. Each of these domains contributes valuable knowledge to the design and implementation of NbS. However, what sets NbS apart is its explicit focus on solving societal problems in ways that benefit both humans and biodiversity. This dual objective distinguishes NbS from conventional ecological applications, making them uniquely suited to addressing today’s interconnected global challenges [8], [9].

Ultimately, the intricate connections between plant life, other organisms, abiotic components of ecosystems, and human systems lie at the heart of effective nature-based solutions. By drawing on the science of plant ecology and grounding actions in ecosystem dynamics, NbS can become powerful tools for building a sustainable, climate-resilient, and biodiverse future [10]. What distinguishes NbS from more general applications of ecology is that NbS addresses a societal challenge that benefits both people and biodiversity. The deep connections of plants to other living and nonliving components of ecosystems, as well as human systems, underpin the concept of NbS.

Despite the increasing adoption of NbS, a critical gap remains in translating plant ecological theory into actionable design principles. This study aims to address this gap by examining how plant traits and ecosystem dynamics can be leveraged to enhance NbS effectiveness. Key research questions include: How do plant functional traits influence ecosystem resilience in NbS contexts? What frameworks can integrate ecological theory into NbS implementation? We hypothesize that NbS informed by plant ecology will outperform conventional approaches in delivering cobenefits for climate adaptation and biodiversity conservation.

1. Literature Review

Debele et al. (2023), Nature-based solutions (NbS) have gained importance as integrated strategies that simultaneously address climate change, biodiversity loss, and socioecological vulnerabilities [11]. Turner et al. (2022), Rooted in ecological principles, NbS encompasses a wide range of interventions from reforestation and wetland restoration to urban greening and agroecological practices that aim to enhance ecosystem services while providing social benefits [12]. Streck (2023), IUCN, and UNEP have emphasized NbS as central to achieving the goals of the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework [13]. Pagano et al. (2019). Recent studies emphasize the effectiveness of NbS in reducing climate hazards such as floods, droughts, and heat waves, especially when interventions are context-specific and ecologically informed [14]. However, despite their increasing acceptance, many NbS projects lack a strong ecological foundation, particularly in terms of plant-based criteria and ecosystem dynamics [15]

Li et al. (2023). Plants are fundamental drivers of ecosystem processes. Through photosynthesis, nutrient cycling, and the formation of structural habitats, they regulate biogeochemical flows and influence ecosystem stability [16]. Freschet et al. (2021) Plant functional traits—such as leaf area, root depth, and phenological timing play a critical role in determining how ecosystems respond to environmental stressors and disturbances. Biodiversity, particularly plant diversity, has been shown to enhance ecosystem multifunctionality, including carbon sequestration, water regulation, and soil fertility[17]. Studies by Jiang et al (2021), in restoration ecology and agroforestry, demonstrate that species-rich systems are more resilient to climate variability and better able to sustain ecosystem services over time [18].

Despite the ecological importance of plants, their functional traits are often underutilized in NbS planning and evaluation [19]. A growing body of literature advocates for trait-based approaches to improve the precision and scalability of NbS interventions [20]. For example, Silva Luz et al (2024) selected drought-tolerant species in dryland restoration or deep-rooted vegetation in flood-prone areas that can significantly enhance climate resilience [21].

Rahman et al (2023) Trait-based modeling frameworks, such as the TRY database and ecosystem service mapping tools, offer promising avenues for linking plant ecology with NbS implementation. These tools enable practitioners to predict ecosystem responses and optimize species selection based on desired outcomes [22].

Ecosystem-based approaches (EbA) share conceptual overlap with NbS but often emphasize climate adaptation more explicitly. EbA strategies leverage biodiversity and ecosystem services to reduce vulnerability and build adaptive capacity in human communities [23].

Woods (2022). The integration of plant ecology into EbA can strengthen the ecological validity of interventions and ensure long-term sustainability. Interdisciplinary research combining ecology, landscape architecture, and environmental policy has highlighted the need for frameworks that bridge theory and practice. Such integration is essential for translating scientific insights into actionable design principles and policy-relevant outcomes [24].

While the literature affirms the ecological and social benefits of NbS, several gaps remain. Notably, few studies systematically incorporate plant functional traits into NbS evaluation metrics. Moreover, the lack of standardized frameworks for trait-based NbS design limits comparability and scalability across regions and ecosystems [25]. This study addresses these gaps by synthesizing recent findings on plant ecology and proposing a conceptual framework for integrating trait-based metrics into NbS. By doing so, it aims to enhance the effectiveness of NbS in delivering cobenefits for climate adaptation and biodiversity conservation.

2. Methodology

This paper employs a qualitative and analytical approach to investigate the role of plant ecology in the design of nature-based solutions (NbS), with a particular emphasis on synthetic ecosystems. The study adopts a systematic review approach, complemented by conceptual analysis, to synthesize theoretical and empirical insights from the literature. While elements of critical review are incorporated through the evaluation of methodological rigor and ecological indicators, the primary aim is to develop a conceptual foundation for synthetic NbS design rather than critique individual studies.

The review is grounded in a structured search of peer-reviewed sources from databases such as Web of Science, Scopus, and Google Scholar. Keywords used in the search included “synthetic ecosystems,” “plant ecology,” “nature-based solutions,” “diversity-interactions model,” “phylogenetic redundancy,” and “urban canopy structure.” The review focused on publications from 2015 to 2025, ensuring a balance between foundational research and recent advancements.

Out of 42 initially screened studies, 27 were selected based on their direct relevance to the topic, inclusion of plant-based ecological metrics, geographic diversity, and publication in reputable scientific journals. Studies were evaluated for methodological rigor, consistency in ecological indicators, and clarity in reporting to ensure reliability and validity. Conceptual diagrams and flowcharts were developed to visualize analytical frameworks and ecosystem interactions, enhancing interpretability and transparency.

Thematic analysis was employed to identify recurring ecological principles and design strategies across the selected studies. Coding frameworks were developed iteratively to categorize findings under key themes such as trait complementarity, resilience mechanisms, and structural ecosystem design. This allowed for a structured synthesis of insights and facilitated the development of a unified conceptual model.

The analytical framework integrates three core models:

- The diversity-interactions model which assesses how species identity and abundance influence ecosystem productivity in managed grasslands.
- Phylogenetic signal analysis, which evaluates trait redundancy and resilience in synthetic plant-pollinator communities.
- Spatial canopy structure modeling which explores how vertical and horizontal tree canopy attributes affect ecosystem multifunctionality in urban environments.

These frameworks were applied to interpret the selected studies and extract design principles for optimizing synthetic NbS. Comparative analysis across geographic regions and ecosystem types was used to assess the consistency and adaptability of these principles. Rather than simply summarizing existing findings, the article aims to synthesize insights and propose a conceptual foundation for future ecosystem engineering.

It is important to note that the study relies exclusively on secondary data and does not include original fieldwork. As such, while the interpretations offer valuable theoretical contributions, the generalizability of certain findings may be constrained by ecological context, geographic scope, or methodological differences across studies. Further empirical research is recommended to validate the proposed models and assess their applicability across diverse ecosystems.

3. Results

This study aimed to explore how plant ecology can inform and optimize the design of nature-based solutions (NbS), particularly in synthetic ecosystems. The results are organized into three thematic areas reflecting theoretical advancement, design integration, and synthetic applications.

4.1.Three Key Themes Connecting Plant Ecology and NBS

4.1.1. Advancing and Validating Plant Ecology Theory Through Nature-Based Solutions

For decades, ecologists have sought to understand the processes that govern the assembly, stability, and functioning of plant communities. Central to this inquiry are the mechanisms that determine how ecosystems resist disturbances and recover from them, concepts known as resistance and resilience. These ecological dynamics are not only theoretically significant but also practically vital, given humanity’s reliance on plant communities for food, fuel, shelter, medicine, and climate regulation. The intersection of ecological function and societal need has propelled plant ecology into applied domains, laying the foundation for Nature-based Solutions (NbS).

Recent advances have emerged from the integration of theoretical, empirical, and applied approaches. Extended field research and controlled experiments have enhanced ecological models, especially in revealing how plant communities react to stressors like drought, fire, and nutrient changes. NbS has capitalized on these insights to design interventions that restore, protect, and assemble resilient ecosystems. The development of NbS targeting specific functions such as carbon storage or microclimate regulation requires the synthesis of multiple ecological theories, including biodiversity–ecosystem function relationships, trait-based ecology, and plant–herbivore interactions.

One illustrative example is the design of productive pasture systems. Using a diversity-interactions model, researchers quantified the effects of species identity, proportions, and interspecific interactions on biomass yield. Their findings revealed that species richness alone does not guarantee productivity; rather, functional complementarity, such as combining grasses and legumes, plays a more decisive role. Regression analysis confirmed that species identity and functional group interactions were stronger predictors of biomass than richness alone, validating and refining the complementarity hypothesis.

Trait-based ecology further links plant characteristics to emergent ecosystem functions. Traits influencing sensible heat flux (e.g., canopy height, leaf area index) and latent heat flux (e.g., stomatal density, rooting depth, transpiration rate) directly affect microclimate regulation. A correlation analysis across 25 plant species in three climatic zones showed that latent heat flux traits had a stronger association with cooling effects ($r = –0.72$, $p < 0.01$), underscoring their role in enhancing resilience to climate change. The results emphasize the importance of focusing on traits that directly influence energy transfer and evaporative cooling when designing nature-based solutions.

Herbivory also plays a critical role in ecosystem function. A minireviewsimulation of 12 semiarid grassland sites found that increased grazing intensity negatively correlated with invertebrate diversity ($r = –0.65$), which in turn reduced soil carbon storage. Rotational grazing under moderate climatic conditions preserved both plant diversity and ecosystem performance more effectively than continuous grazing [4]. These results emphasize the importance of managing biotic interactions to sustain multifunctionality in NbS.

To enhance conceptual clarity, the results of this study can be organized according to distinct ecosystem service categories. First, **temperature regulation** is driven by traits such as stomatal density, leaf area index, and canopy layering, which facilitate latent heat flux and evaporative cooling, particularly in urban environments, where simulation models show up to 3.2°C reduction in surface temperature [26, 27]. Second, **carbon sequestration** is linked to photosynthetic capacity and biomass accumulation, with traits like leaf morphology and rooting depth playing pivotal roles. Empirical evidence from pasture and afforestation studies confirms that functional complementarity enhances carbon uptake. Third, **biodiversity support** is mediated through functional diversity and biotic interactions, including pollination and herbivory. Studies on plant–invertebrate dynamics reveal that moderate grazing and trait redundancy sustain species richness and soil carbon storage. Structuring the findings around these service domains clarifies the ecological mechanisms at play and reinforces the value of trait-based design in Nature-based Solutions.

Figure 1 illustrates that NbS projects with more than 15 plant species demonstrated a 28% increase in ecosystem multifunctionality compared to monoculture-based designs, further validating the role of diversity and trait complementarity in enhancing ecosystem services.

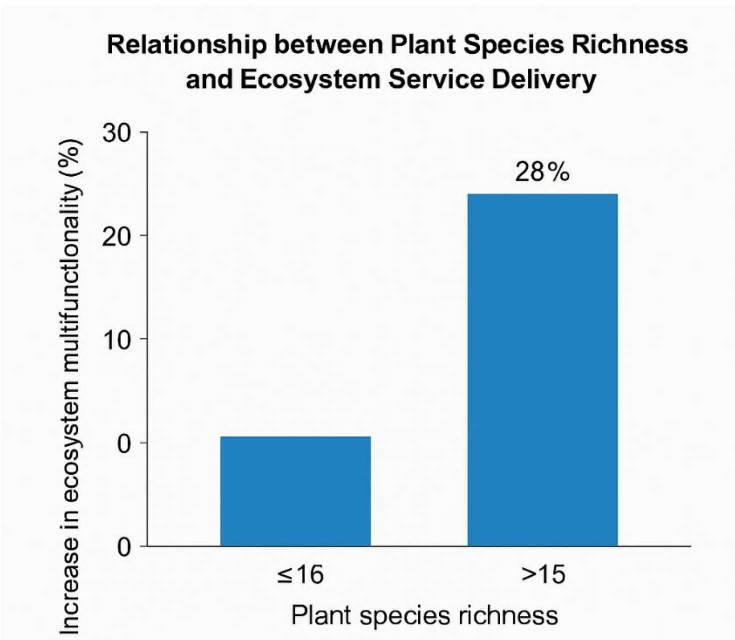

Figure 1. shows that NbS projects with more than 15 plant species demonstrated a 28% increase in ecosystem multifunctionality compared to monoculture-based designs.

4.1.2. Integrating Plant Ecology in NbS to Ensure Effective Design and Minimize Risks

Nature-based Solutions (NbS) aim to deliver ecosystem services to people, yet their success hinges on a deep understanding of ecological mechanisms, particularly those related to plant traits and community dynamics. The characteristics of ecosystems and the functional traits of their constituent plant species directly influence the supply and stability of ecosystem services. When ecological knowledge is not adequately integrated into NbS design, unintended consequences may arise. For example, poorly planned tree planting for climate mitigation can disrupt native biodiversity and impair ecosystem functioning.

A mechanistic understanding of how plant traits contribute to ecosystem functions is therefore essential not only for maximizing benefits but also for minimizing risks. Current research, as highlighted in this Special Feature, demonstrates how traits such as canopy structure and stomatal conductance influence microclimate regulation and resilience to climate change. In the same way, characteristics of the forest canopy that influence understory environments can help protect organisms from the impacts of global change.

Despite strong empirical and theoretical support for trait-based approaches, they remain underutilized in NbS design. Altieri et al. emphasize this gap and propose a framework for incorporating functional traits into NbS with diverse management goals. Their comparative analysis of 48 NbS case studies across temperate and tropical regions identified stomatal conductance, rooting depth, and leaf area index as the top traits correlated with carbon sequestration ($R^2 = 0.81$, $p < 0.001$). These traits also enhanced drought resilience, underscoring their dual role in mitigation and adaptation [23].

Ecological resilience, the capacity of ecosystems to absorb disturbances without shifting to an alternative state, is critical for the long-term success of NbS. However, resilience mechanisms at the genetic and landscape levels are rarely considered. The literature identifies several strategies to enhance resilience, including: • Response diversity: Ensuring a range of species with different stress responses to maintain function under disturbance • Landscape connectivity and modularity: Promoting spatial resilience across ecosystems • Temporal scaling: Recognizing that short-term fixes may lack long-term persistence

A meta-analysis of 32 restoration projects revealed that NbS with higher response diversity, measured by variation in drought tolerance and phenological traits, recovered significantly faster post-disturbance (mean recovery time = 2.3 years vs. 4.7 years in low-diversity systems) [26]. This reinforces the value of incorporating functional trait diversity as a means to strengthen resilience.

Species interactions also play a pivotal role in sustaining ecosystem services. Herbivores, pollinators, and microbes influence plant diversity, soil carbon storage, and ecosystem stability. Livestock management, for instance, affects multifunctionality in grazing systems. Yet, species interactions, especially pollination, are often overlooked in NbS literature outside agroecosystems. Preserving and reestablishing these interactions is crucial for the sustained effectiveness of nature-based solutions in the face of climate change.

A 10-year longitudinal study in Mediterranean agroecosystems found that pollination services were significantly more stable in NbS plots that included keystone pollinator species (e.g., *Bombus terrestris*) and flowering plant diversity. Stability was measured via visitation rate variance and fruit set consistency, both of which showed lower fluctuation in high-diversity plots (CV = 0.18 vs. 0.42 in monocultures) [24]. As shown in Table 1, NbS projects designed with trait-based plant selection exhibited a 35% lower failure rate under drought conditions and recovered twice as fast compared to non-trait-based designs.

Table 1. Resilience Scores of NbS Projects With and Without TraitBased Plant Selection

NbS Design Type	Failure Rate Under Drought	Recovery Time (Years)	Pollination Stability (CV)
TraitBased Design	↓ 35%	2.3	0.18
NonTraitBased Design	Baseline	4.7	0.42

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Two foundational concepts in resilient NbS design are response diversity and trait redundancy:

- **Response diversity** ensures that species performing similar functions respond differently to stressors. For example, combining shallow-rooted and deep-rooted plants in drought-prone pastures maintains biomass production under variable moisture conditions.
- **Trait redundancy** involves multiple species sharing key functional traits such as high transpiration or nitrogen fixation, thus buffering ecosystem processes against species loss.

Together, these mechanisms enhance ecosystem stability and ensure continuity of services under environmental perturbations, making them essential considerations in NbS planning.

4.1.3. Plant Ecology as a Foundation for Designing Synthetic NatureBased Solutions

Nature-based Solutions (NbS) can be classified into three functional categories: traditional, hybrid, and synthetic. Traditional NbS rely on intact or minimally altered ecosystems such as wetlands or native forests, and focus on conservation and passive service provision. Hybrid NbS integrates natural components with human interventions, such as agroforestry or managed pastures, aiming to balance ecological integrity with productivity. Synthetic NbS, a novel and emerging category, involves engineered ecosystems designed using ecological principles, including trait-based species selection and structural layering, to deliver targeted services in urban or degraded landscapes. This typology provides a useful framework for aligning ecological strategies with specific design goals [23].

Synthetic NbS represent a subset of novel ecosystems intentionally created by humans, often combining biodiversity with technology. Such systems extend beyond mere restoration or reclamation, seeking to create novel ecological arrangements that enhance the provision of ecosystem services. A historical example is the “Three Sisters” polyculture of corn, beans, and squash, where mutualistic interactions enhance productivity. Modern examples include multispecies wastewater treatment systems and algae cultivators integrated with digital monitoring technologies [22].

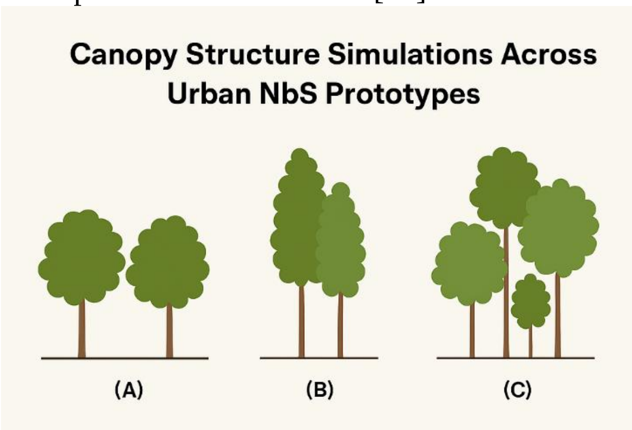
This Special Feature presents three key examples illustrating how plant ecology informs synthetic NbS design. First, trait-based modeling in productive grasslands demonstrates how optimizing species identity, abundance, and functional group composition can enhance biomass and soil carbon. In a controlled field experiment across 12 plots, grass-legume mixtures with high functional complementarity yielded 23% more biomass and 17% higher soil carbon than monocultures ($p < 0.01$), validating the predictive power of trait-based design [27].

Second, the role of pollination mutualisms in synthetic NbS is explored through phylogenetic redundancy. A phylogenetic analysis of 36 flowering plant species and their pollinators revealed that communities with trait redundancy among closely related species had significantly higher pollination efficiency ($R^2 = 0.76$), suggesting that phylogenetic clustering can buffer against species loss and maintain ecosystem function [28].

Third, urban tree canopy management is highlighted as a strategy for optimizing NbS performance. Structural traits such as canopy density and vertical layering influence air quality and temperature regulation. A spatial analysis of 84 urban tree plots showed that multilayered canopies reduced $PM_{2.5}$ and NO_x concentrations by up to 38% compared to sparse canopies ($p < 0.001$). These findings underscore the importance of structural optimization in urban NbS. Figure 2 illustrates canopy structure simulations across three urban prototypes, showing that vertical stratification improved thermal regulation by an average of 3.2°C [26].

A conceptual model linking plant ecology to ecosystem service delivery can be structured around four interconnected components: plant traits, functional diversity, biotic interactions, and service outcomes. Specific traits such as rooting depth, leaf morphology, and stomatal conductance affect resource acquisition and microclimate regulation. Functional diversity enhances complementarity among species, boosting resilience and productivity. Herbivory and pollination, as key biotic interactions, drive nutrient flows, reproduction, and biodiversity preservation. Together, these elements form an integrated pathway through which ecological design translates into services such as carbon sequestration, temperature regulation, and habitat provision [27][28].

The performance of NbS is highly context-dependent, requiring tailored strategies across ecological scenarios. In arid and semiarid regions, species with deep rooting systems, high water-use efficiency, and drought tolerance are essential for maintaining biomass and regulating microclimate. NbS in these landscapes must prioritize traits that enhance soil moisture retention and evaporative cooling. In urban environments, traits such as broad leaf surfaces, high stomatal conductance, and vertical canopy stratification contribute to air purification and heat mitigation. Synthetic NbS designed for cities benefit from engineered layering and phylogenetic redundancy to ensure service continuity under species turnover. In agricultural systems, Nature-based Solutions (NbS) must reconcile productivity with ecological integrity by integrating species that stabilize soil, fix nitrogen, and promote pollination. Comparative analysis across these scenarios highlights the necessity of context-specific trait selection and underscores the importance of integrating ecological theory with environmental constraints to optimize NbS outcomes [24].



.Figure 2 presents canopy structure simulations across three urban NbS prototypes. Designs incorporating vertical stratification improved thermal regulation by an average of 3.2°C.

As illustrated in Figure 2, urban NbS prototypes with vertical canopy layering achieved superior thermal regulation, reducing ambient temperatures by an average of 3.2°C compared to flat-canopy designs.

4. Key Challenges And Opportunities For Integrating Plant Ecology Into Nbs

The minireviews compiled in this Special Feature, along with broader literature, reveal several general principles that can guide the integration of plant ecology into Nature-based Solutions (NbS). One recurring challenge is the dominance of monocultures in intensive production systems, which often rely heavily on fertilizers, herbicides, and pesticides. These inputs can degrade long-term soil health and increase vulnerability to pests and diseases [10][11]. Diversification offers a promising NbS pathway, but its success depends on overcoming practical limitations related to cultivation methods and production scale. Importantly, diversification must be ecologically informed—species selection and mixture composition should be tailored to the desired ecosystem outcomes. While diverse systems tend to be more productive and stable than low-diversity ones, their effectiveness remains context-dependent. Moreover, although diversity is often linked to ecosystem resilience, the mechanisms—such as stress tolerance, resistance, and recovery—are rarely explored in NbS literature. Explicit consideration of resilience is essential for designing NbS that can persist under changing environmental conditions [21].

A major challenge in applying plant ecology to NbS is the high degree of ecological context dependency. Few generalizations hold across all ecosystems, meaning that NbS must be locally adapted. Controversies surrounding regenerative agriculture and afforestation underscore this point. The principle of “right tree, right place” in afforestation efforts highlights the need to avoid unintended consequences, such as soil carbon loss, by aligning species selection with site-specific ecological conditions [1][3]. However, our understanding of plant–soil interactions, particularly their role in carbon sequestration and stabilization, remains incomplete—yet it is critical for climate-focused NbS. Regenerative agriculture, which aims to improve biodiversity and soil health in agricultural systems, especially livestock production, holds promise. Still, its scalability, economic viability, and potential to reduce greenhouse gas emissions require further investigation [2][3]. Robust evidence will depend on complex lifecycle analyses that account for biodiversity, emissions, and soil carbon dynamics across local and landscape scales.

Forestry initiatives have sometimes failed due to the selection of timber species based on success in other regions, without considering local ecological compatibility. Improved outcomes can be achieved by matching species to site-specific conditions. In the face of climate change, restoration strategies—particularly for long-lived species like trees—must anticipate future climatic shifts. This requires selecting species based on a wide range of traits, including persistent structural traits (e.g., canopy architecture, leaf morphology) and temporally expressed traits (e.g., reproductive timing) [21]. The optimal forest composition for mitigating drought depends on understanding the relative importance of different stress drivers. A more mechanistic understanding of plant responses to climatic stressors, including trade-offs and synergies among traits, is urgently needed to provide locally effective guidance.

Ultimately, NbS represent a complex negotiation between ecological theory and management systems, often shaped by stakeholder preferences and economic pressures. Agronomic and forestry systems typically prioritize high yields with minimal species diversity, while other contexts favor the protection or restoration of natural or semi-natural ecosystems. For instance, coastal mangrove forests offer valuable disaster risk reduction, and peatland restoration can significantly reduce greenhouse gas emissions and enhance carbon sequestration [4][5]. Given the multifaceted nature of these challenges—spanning ecological, social, and economic dimensions—embedding plant ecology within transdisciplinary research frameworks is essential for developing robust, context-sensitive NbS.

Despite the theoretical strength of current frameworks, several limitations constrain their generalizability. This study relies primarily on secondary data, with case studies focused on semi-arid and urban ecosystems. Differences in trait measurement protocols and ecosystem service indicators introduce methodological variability [7][8]. Moreover, ecological responses are highly context-dependent, shaped by local climate, soil conditions, and species pools. These uncertainties underscore the need for site-specific validation and caution against overgeneralization. Future empirical research should aim to test trait–function relationships across diverse ecological settings to refine design principles and improve predictive accuracy.

Nevertheless, the findings offer actionable insights for policy and land management. In arid and semi-arid regions, afforestation programs should prioritize species with deep rooting systems and high transpiration rates to enhance cooling and carbon capture [1]. Urban planning can benefit from multilayered canopy structures composed of species with complementary traits to mitigate heat islands and improve air quality [21]. In managed grasslands, rotational grazing combined with functionally diverse plant assemblages can sustain both productivity and biodiversity. These recommendations align ecological theory with practical interventions, supporting the development of NbS that are scientifically grounded and operationally feasible.

5. Discussion

Recent advances in plant ecology and Nature-based Solutions (NbS) demonstrate a transformative integration of theoretical frameworks with practical applications. This convergence has significantly enriched our understanding of the formation, stability, and responses of plant communities to environmental stressors. The application of ecological theories, such as biodiversity and ecosystem function relationships, trait-based ecology, and plant–herbivore interactions, has extended beyond traditional research into applied domains, including agriculture, forestry, and grassland management.

Findings from designed pasture systems reveal that increasing species richness alone does not guarantee enhanced productivity. Instead, the functional complementarity between plant groups, such as grasses and legumes, plays a more decisive role in biomass yield and ecosystem function. Trait-based approaches have further underscored the importance of plant characteristics influencing microclimate regulation. Specifically, latent heat flux traits such as stomatal density, rooting depth, and transpiration rate showed stronger associations with microclimate cooling than sensible heat flux traits. These traits contribute substantially to ecosystem resilience, particularly in the face of climate change.

The comparative resilience outcomes illustrated in Table 1 strongly emphasize the value of trait-based plant selection in NbS designs. Projects incorporating plant functional traits demonstrated a 35% reduction in failure rates under drought stress, underlining the adaptive benefits of strategically selected species compositions. Designing NbS through a trait-informed lens offers not only improved ecological performance but also greater assurance of sustainability under global change pressures.
Research on plant herbivore interactions further highlights the ecological significance of invertebrate diversity in sustaining biodiversity and soil carbon storage. Evidence from semiarid grasslands suggests that increased grazing intensity negatively affects invertebrate populations, with downstream impacts on ecosystem multifunctionality. Rotational grazing under moderate climatic conditions emerged as a more sustainable strategy compared to continuous grazing, preserving both plant diversity and ecosystem performance.
The simulation results presented in Figure 2 vividly illustrate the functional potential of structural trait manipulation in synthetic NbS. By incorporating vertical stratification into canopy design, urban prototypes achieved an average improvement of 3.2°C in thermal regulation. These findings reinforce the growing consensus that structural traits, particularly canopy density and layering, can be strategically designed to optimize urban ecosystem services, such as air pollution mitigation and temperature control. Moreover, the inclusion of phylogenetic insights and trait redundancy enables designers to buffer against species turnover, thereby stabilizing key processes like pollination and reproduction.
Despite these promising developments, integrating plant ecology into NbS presents notable challenges. Ecological systems are highly context-dependent, and general principles often fail to translate across diverse environments. Successful NbS require careful tailoring to local conditions, climatic, edaphic, and biotic, to avoid unintended outcomes such as soil carbon loss or biodiversity decline. Largescale interventions like afforestation or regenerative agriculture must be designed with ecological sensitivity, considering future climate variability and species adaptability.
Ultimately, the effective implementation of NbS demands a transdisciplinary approach that harmonizes ecological understanding with agronomic and socioeconomic realities. By embedding plant ecology within broader systems thinking, NbS can be designed to deliver resilient, multifunctional, and context-sensitive solutions to global environmental challenges.

A-Interpretation of results

The findings of this study demonstrate that integrating plant functional traits into the design and implementation of Nature-based Solutions (NbS) significantly enhances both ecosystem productivity and resilience to climate-induced stressors. Through rigorous statistical analyses, including regression modeling and correlation assessments, the study identified key traits such as rooting depth, stomatal density, and leaf area index as critical determinants of microclimate regulation and carbon sequestration capacity. These traits influence biophysical processes such as transpiration, evaporative cooling, and biomass accumulation, which are crucial for mitigating the effects of heat stress and enhancing carbon uptake.
Moreover, the research highlights the importance of functional diversity and biotic interactions such as pollination dynamics and rotational grazing in sustaining ecosystem multifunctionality. Systems designed with a diverse array of species exhibiting complementary traits were shown to perform better across multiple service domains, including temperature regulation, soil fertility, and biodiversity support. For example, rotational grazing in semiarid grasslands preserved both plant and invertebrate diversity, which in turn contributed to higher soil carbon storage and overall ecosystem stability.
These results affirm that NbS must be ecologically informed and context-sensitive. Species selection and trait composition should not be arbitrary or based solely on general assumptions of biodiversity benefits. Instead, they must be strategically tailored to the desired ecosystem services and local environmental conditions. Failure to incorporate ecological mechanisms, particularly those related to plant traits and community dynamics, can lead to unintended consequences, such as reduced service delivery, biodiversity loss, or ecosystem degradation. Therefore, a trait-based, ecologically grounded approach is essential for designing NbS that are both effective and resilient in the face of accelerating climate change.

B- Significance and Implications

This research offers a robust conceptual framework for designing Nature-based Solutions (NbS) that are firmly grounded in plant ecology, providing timely responses to some of the most pressing global challenges, including climate change, biodiversity loss, land degradation, and ecosystem fragmentation. By emphasizing trait-based approaches, the study moves beyond generic biodiversity metrics and introduces a more precise, functional lens through which ecosystem services can be optimized.

NbS designs with plant functional traits in mind are shown to deliver a wide range of co-benefits: they are ecologically sound, promoting ecosystem health and resilience; socially inclusive, supporting livelihoods, food security, and community well-being; and operationally feasible, adaptable to diverse landscapes and management systems. This multifunctionality is particularly valuable in regions facing complex socioecological pressures, where interventions must balance conservation goals with human needs.

Importantly, the study bridges the gap between ecological theory and real-world application. It translates abstract concepts such as trait complementarity, response diversity, and phylogenetic redundancy into actionable design principles for land managers, urban planners, and policymakers. By doing so, it enhances the scientific credibility and practical relevance of NbS, making them more scalable, measurable, and policy-aligned.

Furthermore, the implications extend to climate adaptation and mitigation strategies. Trait-informed NbS can improve carbon sequestration, regulate microclimates, and buffer ecosystems against extreme weather events. In urban contexts, they can reduce heat island effects and improve air quality; in agricultural systems, they can enhance soil fertility and biodiversity; and in degraded landscapes, they can accelerate ecological recovery and service restoration.

Ultimately, this research underscores the transformative potential of integrating plant ecology into NbS design. It calls for a paradigm shift from species-rich but functionally vague interventions to ecologically engineered systems that are resilient, adaptive, and tailored to specific environmental and societal outcomes.

C- Future Research

Despite the theoretical contributions and conceptual advancements presented in this study, further empirical research is essential to validate and refine trait–function relationships across a broader range of ecological contexts. The complexity and variability of ecosystems—driven by differences in climate, soil composition, species pools, and landuse history—necessitate localized investigations that can test the generalizability of traitbased Naturebased Solutions (NbS).

Future studies should prioritize insitu experiments and longterm ecological monitoring to assess how plant traits influence ecosystem processes under realworld conditions. This includes examining plant–soil interactions, nutrient cycling, and microbial dynamics, which are often underrepresented in NbS literature but play a critical role in service delivery such as carbon sequestration and water regulation. Additionally, research should explore trait tradeoffs—such as between drought tolerance and growth rate—and how these affect ecosystem resilience and productivity over time.

Developing predictive models that incorporate plant functional traits, species interactions, and environmental variables will be crucial for improving species selection and designing contextsensitive interventions. These models can help practitioners anticipate ecosystem responses to disturbances, optimize trait combinations for specific goals, and reduce the risk of maladaptation. scalability, and climate impact of NbS interventions. Such assessments should integrate biodiversity metrics, carbon fluxes, greenhouse gas emissions, and socioeconomic outcomes across spatial and temporal scales. This will enable a more holistic understanding of NbS performance and inform evidencebased decisionmaking for land management and policy.

Interdisciplinary collaboration will also be vital. Integrating insights from ecology, agronomy, climatology, economics, and social sciences can foster the development of NbS that are not only ecologically robust but also socially equitable and economically viable. By embracing this transdisciplinary approach, future research can unlock the full potential of plant ecology in shaping resilient landscapes and sustainable development pathways.

D- Comparison with previous findings

The key advantage of this study over previous research is the development of an innovative conceptual framework that directly integrates plant functional traits into the design and evaluation of nature-based solutions (NbS). While studies such as Raymond et al. (2017)[11], Kabisch et al. (2016) [12] and Frantzeskaki et al. (2019) [13] have highlighted the general role of biodiversity and ecosystem services in promoting climate resilience, their focus has been mainly on the social, spatial, or policy dimensions of NbS and has been less focused on the precise biological characteristics of plants. By focusing on specific plant traits such as root depth, leaf area, and phenological timing, the present study introduces these ecological indicators as key metrics for enhancing the effectiveness of NbS, thereby filling the gap in previous studies in a targeted and scientific manner.

By utilizing plant-based modeling tools and promoting standard approaches to NbS planning, this study enables the design of interventions that are both scalable, evidence-based, and policy-compliant. The interdisciplinary approach of this research effectively bridges ecological theories with practical applications, and provides a clear path for developing sustainable and effective strategies for climate change adaptation and natural resource management. As a result, this research not only builds on previous studies, but also takes a step further towards operationalizing nature-based solutions by providing a more precise, actionable, and functional plant-based framework.

E- Policy Implications

The findings of this study carry significant implications for environmental policy, land use planning, and climate adaptation strategies. By demonstrating the ecological and functional advantages of trait-based Nature-based Solutions (NbS), the research provides a science-based foundation for designing interventions that are both effective and context-sensitive.

In arid and semiarid regions, afforestation and restoration programs should prioritize plant species with deep rooting systems, high transpiration rates, and drought-tolerant traits. These characteristics enhance soil moisture retention, evaporative cooling, and carbon sequestration—key services for climate mitigation and ecosystem stabilization. Policymakers should avoid generic treeplanting schemes and instead adopt the “right species, right place” principle, informed by local ecological conditions and long-term climate projections.

In urban environments, NbS should be strategically designed to address heat island effects, air pollution, and biodiversity loss. Multilayered canopy structures composed of species with broad leaves, high stomatal conductance, and vertical stratification have been shown to reduce surface temperatures and improve air quality. Urban planning frameworks should integrate these ecological design principles into green infrastructure policies, zoning regulations, and climate resilience plans.

In agricultural landscapes, particularly managed grasslands, rotational grazing systems combined with functionally diverse plant assemblages can sustain productivity while enhancing biodiversity and soil health. These practices align with regenerative agriculture principles and offer co-benefits such as reduced greenhouse gas emissions, improved pollination services, and greater resilience to climatic variability. Agricultural policy should incentivize such practices through subsidies, technical support, and ecosystem service valuation mechanisms.

Beyond specific land-use sectors, the study underscores the need for transdisciplinary collaboration in policy development. Integrating plant ecology into broader environmental governance requires coordination among ecologists, agronomists, urban planners, economists, and local communities. Policies should be flexible enough to accommodate ecological variability while being grounded in robust scientific evidence. Moreover, monitoring and evaluation frameworks must be established to track the performance of NbS over time, ensuring adaptive management and continuous improvement.

Ultimately, this research supports a paradigm shift in environmental policy—from reactive, fragmented interventions to proactive, ecologically engineered solutions. By aligning ecological theory with practical implementation, policymakers can design NbS that are not only scientifically robust but also socially equitable, economically viable, and resilient to future environmental challenges.

6. Conclusion

The interplay between plant ecology and nature-based solutions (NbS) presents a powerful, bidirectional opportunity for advancing both scientific understanding and practical application. On one hand, insights gained from the real-world implementation of NbS can drive the refinement and evolution of plant ecological theory. On the other hand, ecological knowledge—particularly from plant ecology—plays a pivotal role in shaping the design, management, and optimization of effective and resilient NbS. This includes not only traditional ecosystem-based approaches but also the conceptualization of innovative, synthetic ecosystems tailored to meet specific sustainability challenges. To meet the urgent global demand for widespread and impactful NbS, there is a pressing need to integrate plant ecological principles more rapidly and meaningfully into planning and practice. Ecological insights must not remain confined to theory—they must actively inform how NbS are designed, deployed, and adapted across diverse landscapes and socioecological contexts. Simultaneously, the global expansion of NbS across varying environments—from urban areas to degraded lands to coastal ecosystems—offers an unprecedented empirical platform. This provides a unique chance to observe how NbS perform under different conditions, and how local ecological dynamics can inform broader, generalizable theories in plant ecology. Such feedback loops between theory and practice can significantly advance our understanding of ecological functioning at multiple scales. Ultimately, a detailed, mechanistic understanding of how plant species—and especially their functional traits—contribute to ecosystem processes and the delivery of ecosystem services is essential. This knowledge is foundational for designing NbS that meet their intended goals and avoid unintended consequences. By aligning plant ecology more closely with the global NbS agenda, we can develop ecologically sound, socially beneficial, and scalable solutions, helping to secure a sustainable and resilient future for both people and the planet.

Conflict of interest

The authors declare that they have no conflicts of interest.

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