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REVIEW ARTICLE

A hidden world: The role of non-vascular plants in ecosystem functioning and climate regulation

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Abstract

Non-vascular plants (NVPs) which fall into their general definition, such as bryophytes as well the algae and fungi (that are not plants taxonomically) constitute fundamentally but often forgotten contributors to ecosystem functioning and climate regulation. NVPs are also characterized by a unique suite of physiological and structural attributes contributing to their success in a wide array of frequently harsh habitats despite the lack of vascular tissues such as xylem and phloem. Their ecological roles are soil formation, nutrient cycling, water retention and creation of microhabitats for biodiversity. Furthermore, NVPs are major contributors to global carbon sequestration with bryophytes as the key plant in peatland systems and algae in aquatic including marine ecosystems which help reduce climate warming. However, these organisms are still largely missing from environmental models and conservation management plans as current understanding of their ecological significance is poor. This review compiles actual data concerning the structural and functional diversity among NVPs to emphasize the importance of these organisms in key ecosystem services. It also demonstrates their use in biotechnological areas like phytoremediation, sustainable fertilizers production and climate-resilient habitats restoration. It additionally elucidates new threats to NVPs such as habitat destruction and climate-driven stress, offering a plea for their incorporation into environmental policy and scientific investigation. Two summary tables present their ecological functions and climate-related mechanisms, whereas descriptive figures depict the global distribution and functional roles. The focus on NVPs in the ecological assessment is essential for improving ecosystem stability and for the provision of sustainable responses to climate pressures.

Keywords: bryophytes; carbon sequestration; climate regulation; ecosystem services; non-vascular plants

Introduction

Bryophytes, algae and fungi are evolutionarily distinct lineages, yet they play convergent ecological roles in shaping terrestrial ecosystems. Although these organisms lack specialized vascular tissues like xylem and phloem, they exhibit remarkable ecological adaptability and are integral to sustaining ecosystem balance and functionality (1, 2). In contrast to vascular plants that visibly dominate terrestrial landscapes and scientific literature, NVPs deliver critical ecological services, particularly within nutrient-deficient and environmentally harsh habitats like peatlands, alpine environments, deserts and polar ecosystems.

These plants are essential in primary succession, soil formation, moisture holding and nutrient recycling. For example, bryophytes are capable of sequestering atmospheric inputs and can aid in the stabilization of local microclimates, while algae improve productivity of aquatic eco-systems and regulate numerous biogeochemical processes (3, 4). Similarly, fungi particularly those involved in symbiosis with algae or higher plants (e.g., mycorrhizae and lichens) facilitate nutrient uptake, soil fertility maintenance and control carbon cycling dynamics (5). Global climate change concerns have raised the profile of species such as Sphagnum mosses and heavy large marine algae like kelp for carbon sequestration (6).

Nevertheless, despite their vital ecological and climatic functions, NVPs remain poorly integrated into global environmental models, conservation strategies and assessments of ecosystem services (7, 8). This oversight can be attributed to their subtle physical characteristics, intricate taxonomy and relatively low direct economic utility. However, a growing body of research highlights their crucial contributions to biodiversity preservation, climate moderation and the resilience of ecosystems in the face of environmental change (9).

This review seeks to explore the taxonomic richness and functional roles of NVPs, examine their integral contributions to ecosystem processes and climate regulation, underscore their potential in biotechnological innovations and ecological restoration practices and recommend focused conservation measures to ensure their persistence amid accelerating global environmental change.

Taxonomic and functional diversity of NVPs

Non-vascular organisms (NVOs) encompass bryophytes and algae, while fungi though taxonomically distinct are frequently examined in parallel due to their comparable ecological functions a broad and evolutionarily varied assemblage of organisms, including bryophytes (such as mosses, liverworts and hornworts), algae (both microscopic and macroscopic forms) and fungi particularly lichens and other symbiotic types. While these groups are not united by a common phylogenetic origin, they share structural simplicity, the absence of vascular tissues and ecological adaptations that allow them to thrive in moist, shaded, or environmentally extreme habitats (10, 11).

Bryophytes, which are the most adapted to terrestrial life among NVPs, are characterized by gametophyte-dominant life cycles and are notable for their pioneering role in colonizing barren surfaces thereby initiating soil development and stabilization processes (12). Liverworts and hornworts contribute uniquely within this group, displaying distinct reproductive and cellular traits such as oil bodies and pyrenoids (13). In contrast, algae constitute a polyphyletic group, encompassing organisms that range from single -celled phytoplankton to large seaweed like kelp. In aquatic environments, algae play a pivotal role in driving primary production and generating atmospheric oxygen (14).

Fungi, especially those involved in lichenization with algae or cyanobacteria, are critical to nutrient cycling and serve as reliable bioindicators due to their high sensitivity to environmental fluctuations, such as lichens being used as bioindicators of air pollution (15).

Even though mycorrhizal fungi are not plants, they can be considered to act in a role of non-vascular (and indeed non-seed producing) plants leading to a concept often considering them as NVPs; and due their non-vascular nature for nutrient uptake and reverting soil structure can help (but never replace) in absorption (16).

The variety of NVPs are not only in taxonomy but also have many functional characteristics. They have impressive physiological flexibility which allows high desiccation tolerance in bryophytes and the production of resistant spores or dormant stages that allow them to inhabit habitats completely out of reach for vascular plants like rock surfaces, tree bark, glacier margins and shallow waters (17, 18).

By different morphologies, pigments and symbiotic versus non-symbiotic lifestyles, NVPs make a significant structural and functional complexity in ecosystems. It is critical to gain a deep knowledge of their diversity for assimilating them into ecological modelling and designing biodiversity conservation plans (19).

Ecosystem functions supported by NVPs

NVPs are essential elements in ecosystem function due to their direct and indirect contribution to important ecological processes. Their effects range from soil formation and nutrient cycling to hydrological control and the supplementation of biodiversity, making them important through terrestrial and aquatic systems (20). In this section, we discuss the key ecological services of NVPs with focus on their cornerstone services serving to enhance ecosystem stability and productivity. Lichenized cyanobacteria, for example, are believed to account for close to 50 % of the biologically fixed nitrogen within terrestrial ecosystems and kelp forests around the world collectively sequester ~4.9 Pg.C/year, emphasizing the importance of non-vascular plants (21).

Soil development and structural integrity

Bryophytes and lichens are recognized as primary colonizers of barren surfaces such as bare rock, lava fields and degraded soils. Through a combination of chemical weathering and mechanical disintegration, these organisms initiate the breakdown of geological substrates and help form soil (22). Their ability to trap airborne particles and retain moisture fosters the accumulation of organic matter and facilitates the establishment of microbial life and early vascular plant communities (23).

In arid and semi-arid settings, biological soil crusts (biocrusts) composed of mosses, lichens, algae and fungi play a critical role in mitigating soil erosion caused by wind and water. These crusts improve soil porosity, enhance infiltration and reduce surface runoff, thereby strengthening soil structure and promoting fertility (24, 25).

Nutrient dynamics and hydrological stability

NVPs are key players in biogeochemical processes, particularly in nitrogen and phosphorus cycling. Nitrogen-fixing cyanobacteria present in lichens and mosses enrich nutrient-poor soils by converting atmospheric nitrogen into bioavailable forms (26). Within aquatic environments, algae facilitate nutrient recycling through uptake of inorganic nutrients and release of dissolved organic matter via metabolic processes and decomposition (27).

NVPs also serve as natural water reservoirs, with some species retaining more than 20 times their dry weight in water. This remarkable water retention capacity contributes to hydrological balance in ecosystems such as forests, wetlands and peatlands (28), helping maintain soil moisture during droughts and supporting plant community sustainability.

Habitat structuring and biodiversity promotion

Dense mats formed by NVPs create intricate, multilayered microhabitats that support diverse communities of invertebrates, protists, fungi and microorganisms. These structures provide protection against desiccation, ultraviolet radiation and thermal stress, thereby enhancing biodiversity across both terrestrial and aquatic ecosystems (29, 30). Acting as refugia and resource hotspots, NVPs promote species interactions and strengthen ecosystem resilience, particularly in unstable or nutrient-poor environments, as illustrated in Table 1 and Fig 1.

Moreover, the multifunctional ecological roles of NVPs in climate regulation such as enhancing soil stability, facilitating nutrient cycling and supporting biodiversity are summarized in Table 2.

NVPs and climate regulation

NVPs have garnered growing attention for their multifaceted contributions to climate regulation, including their capacity to sequester carbon, influence albedo and filter atmospheric pollutants. Despite their diminutive size, NVPs atmospheric composition, energy exchange at the Earth's surface and microclimatic stability in both land and aquatic environments (31, 32). This section outlines the principal mechanisms through which NVPs shape both global and localized climate systems.

Carbon sequestration

Bryophytes, most notably sphagnum mosses, are the dominant flora of peatlands, ecosystems that store over 30 % of global terrestrial carbon, despite covering less than 3 % of the earth's surface (33). These mosses impede organic matter decomposition by producing phenolic compounds and maintaining acidic, low-oxygen conditions, which promote long-term carbon accumulation (34).

Table 1. Ecosystem functions supported by non-vascular plants and their ecological significance

Function	Non-vascular plant groups	Ecological role	Ecosystem impact
Soil formation & stabilization	Bryophytes, lichens	Weathering, particulate trapping	Initiates soil formation, reduces erosion
Nitrogen fixation	Cyanobacteria in lichens, mosses	Conversion of atmospheric N to bioavailable forms	Enhances soil fertility
Water retention	*Sphagnum* mosses, liverworts	High water-holding capacity	Supports water availability during dry periods
Microhabitat provisioning	Bryophyte mats, freshwater algae	Habitat for micro fauna and microbial communities	Enhances species richness and ecological resilience
Nutrient cycling	Algae, fungi, lichens	Nutrient absorption and release	Promotes ecosystem productivity

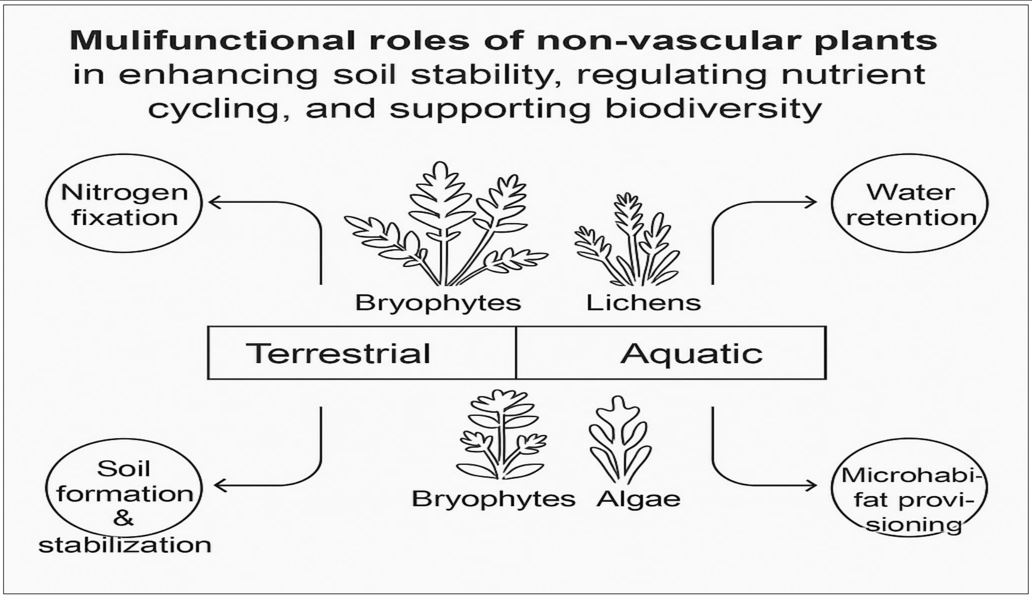

Fig. 1. Multifunctional roles of non-vascular plants in enhancing soil stability, nutrient cycling and biodiversity.

Table 2. Mechanisms by which non-vascular plants contribute to climate regulation

Climate regulation mechanism	Non-vascular plant groups	Underlying biological process	Climate impact
Carbon sequestration	*Sphagnum* mosses, microalgae	CO_2 fixation; peat accumulation; deep-sea carbon deposition	Long-term carbon storage; reduced atmospheric CO_2 levels
Albedo modulation	Bryophyte and lichen mats	Light reflectance and thermal insulation	Reduced surface warming; maintenance of permafrost
Microclimate buffering	Bryophytes, lichens	Moisture retention; surface insulation	Stabilized soil temperatures; protection from desiccation
Pollutant filtration	Mosses, lichens, algae	Passive absorption of pollutants (SO_2, NO_x, heavy metals)	Improved air and water quality; reduced oxidative stress
Ocean-atmosphere CO_2 exchange	Marine algae (e.g., kelp forests)	Photosynthetic uptake and export to deep sediments	Reduced ocean acidification, enhanced carbon sink function

In marine ecosystems, microalgae such as *Macrocystis pyrifera* (giant kelp) serve as effective carbon sinks by capturing atmospheric CO_2 and facilitating its long-term storage in deep ocean sediments after decomposition (35). Similarly, freshwater algae enhance carbon cycling by promoting the deposition of organic materials and altering sediment properties (36).

Thermal regulation and albedo modification

Mats of bryophytes and lichens influence solar reflectivity (albedo), with measured albedo values typically ranging between 0.15-0.25 compared to bare soil at ~0.10 and fresh snow at ~0.80-0.90. Such differences significantly affect surface energy balance and microclimatic conditions (37), particularly in alpine and tundra habitats. These organisms insulate the soil, moderating surface temperatures and reducing heat flux, which in turn supports permafrost stability and extends snow cover duration (38, 39). Such thermal buffering mechanisms are essential in maintaining climate equilibrium in high-latitude environments.

Air purification and pollutant removal

Lichens and mosses demonstrate high efficiency in capturing airborne pollutants, including heavy metals, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which is attributed to their large surface area and passive gas absorption mechanisms. For instance, lichen species such as Parmelia sulcata and *Hypogymnia physodes* are widely recognized bioindicators for assessing air pollution levels. Their dual function as bioindicators and phytoremediators makes them especially valuable in urban and industrial environments impacted by air pollution (40). By accumulating contaminants, they help mitigate environmental toxicity, reduce oxidative stress in neighboring plants and improve overall air quality (41, 42). Key mechanisms and global relevance are summarized in Table 2 and Fig 2.

Fig. 2. Global distribution of NVP-dominated zones and their role in carbon sinks.

Biotechnological and ecological applications of NVPs

NVPs offer considerable promise in the fields of biotechnology and ecological restoration due to their distinctive physiological adaptations, metabolic diversity and symbiotic capabilities. Their structural minimalism, ecological flexibility and rich biochemical profiles render them highly effective for sustainable agricultural practices and environmental cleanup. They are also valuable in wastewater treatment and in the development of climate-adaptive green infrastructure (43, 44).

Phytoremediation and wastewater management

Algae and bryophytes are increasingly being utilized in phytoremediation strategies. Microalgal species such as *Chlorella vulgaris* and *Scenedesmus obliquus* are particularly efficient at removing heavy metals, nitrogen, phosphorus and various organic contaminants from wastewater sources (45). Mosses, known for their extensive surface area and strong pollutant absorption capabilities, are effective components of passive filtration systems, operating without the need for external energy inputs (46).

When integrated into constructed wetlands and biofiltration setups, systems combining mosses and algae greatly improve water quality and enhance nutrient cycling. These environmentally friendly technologies offer scalable, low-cost solutions for decentralized wastewater management, particularly in rural and under-resourced communities (47).

Bio fertilization and soil conditioning

Certain green algae and cyanobacteria contribute to soil health by fixing atmospheric nitrogen, solubilizing phosphorus and synthesizing phytohormones. Incorporation of algal-based biofertilizers into agricultural soils has been demonstrated to improve crop productivity, enhance root systems and increase drought resilience across various farming systems, particularly in staple crops such as wheat, rice and maize (48). Furthermore, bryophyte-derived mulches and composts are under investigation for their potential to retain soil moisture and promote microbial diversity (49).

Medicinal and industrial potential

Algae serve as a rich reservoir of bioactive substances-such as antioxidants, antimicrobial agents and anti-inflammatory compounds that hold significant potential for pharmaceutical, nutraceutical and cosmetic applications (50). Additionally, lichens and fungal endophytes synthesize secondary metabolites with demonstrated antibiotic and anticancer activities (51).

Recent innovations have explored the use of moss extracts in sun-protective skincare, fungal pigments as biodegradable dyes and lichen-based compounds as natural preservatives and bio pesticides (52, 53).

Climate-resilient restoration and green infrastructure

Due to their adaptability to environmental stress, minimal nutrient requirements and physiological plasticity, NVPs are increasingly utilized in green roofs, the restoration of biological soil crusts and the rehabilitation of post-mining landscapes. Mosses and lichens play a crucial role in stabilizing eroded soils, fostering ecological succession and boosting local biodiversity (54).

In regions exposed to climate extremes, the introduction of bryophytes or algae into degraded soils has been demonstrated to enhance carbon sequestration and accelerate vegetation recovery, especially in arid and semi-arid environments (55, 56) (Fig. 3).

Threats to NVPs and conservation imperatives

Although NVPs provide critical ecological services and hold emerging biotechnological potential, they face mounting pressures from both pollution and climate change. For instance, atmospheric pollutants such as SO_2 disrupt lichen physiology by impairing photosynthesis and damaging symbiotic relationships, while climate-driven permafrost thaw alters hydrological regimes that directly affect bryophyte survival and distribution. Moreover, their small size, inconspicuous morphology and limited detectability in ecosystems often lead to their exclusion from environmental monitoring and conservation frameworks (57, 58).

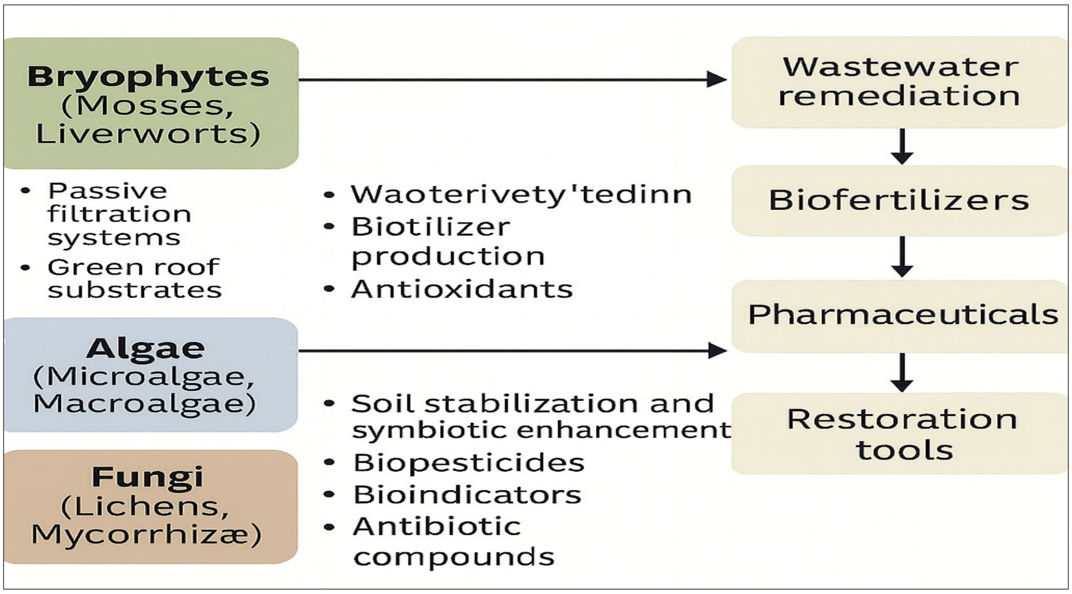

Fig. 3. Biotechnological and ecological applications of non-vascular plants across different sectors.

Habitat degradation and land-use transformation

Land conversion through deforestation, intensified agriculture, urban sprawl and mining operations has led to widespread habitat destruction critical for NVP persistence. Species like bryophytes and lichens which require undisturbed substrates and consistent microclimatic conditions are particularly sensitive to disruptions in humidity, light availability and substrate integrity (59). Algal populations in freshwater and marine systems are likewise threatened by nutrient overloading (eutrophication), sediment deposition and fragmentation of aquatic habitats (60).

Climatic shifts

Climate change exerts multifaceted pressures on NVPs. While some bryophytes can tolerate drying, prolonged drought conditions and hydrological variability still pose significant risks (61). Mosses in alpine and polar zones are increasingly impacted by melting permafrost and the spread of woody vegetation into previously open habitats (62). Coastal macroalgae and lichens are vulnerable to ocean warming, acidification and sea-level rise, all of which alter the structural and chemical conditions of their habitats (63).

Pollution and abiotic stressors

Environmental pollutants particularly airborne toxins like sulfur dioxide (SO_2) and heavy metals have significantly reduced lichen diversity, especially in densely populated or industrial areas (64). Aquatic algae are also susceptible to a range of pollutants, including microplastics and endocrine-disrupting chemicals, which negatively affect their photosynthetic activity, growth rates and ecological interactions within food webs (65).

Policy gaps and research neglect

NVPs receive inadequate attention in national and international biodiversity policies, as well as in the design of conservation zones. Despite their roles as keystone species and sensitive indicators of ecosystem health, they are frequently excluded from ecological restoration frameworks (66). Efforts to protect NVPs are also impeded by limited taxonomic clarity, insufficient funding and a global shortage of trained experts in fields such as bryology, phycology and lichenology (67).

Conservation recommendations

Ensuring the long-term survival of NVPs and safeguarding the ecosystem services they provide requires their explicit inclusion in both national and international conservation frameworks. A multi-pronged strategy should include:

- Integrating NVPs into biodiversity monitoring programs.
- Protecting microhabitats where NVPs thrive such as tree bark, rocky outcrops and shaded wetlands.
- Supporting research on NVP taxonomy, physiology and distribution.
- Applying NVPs in ecological restoration and green infrastructure projects.
- Raising awareness through education, citizen science and outreach campaigns.

Collectively, these measures will enhance ecological stability, conserve biodiversity and foster climate resilience. Importantly, NVPs should be embedded within international frameworks such as the Convention on Biological Diversity (CBD), the IUCN Red List, the Ramsar Convention and the UN Sustainable Development Goals (SDGs) to ensure their recognition and long-term protection (68, 69).

Conclusion

In conclusion, non-vascular plants are vital yet underrepresented in both science and policy. Their role in carbon regulation, soil fertility and climate resilience underscores the need for greater recognition. Future efforts must integrate them into restoration and conservation agendas to build more resilient ecosystems in the face of global change.

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Authors' contributions

NAM proposed the research idea, contributed to the preparation of the proposal, and collected the specimens. AMI was responsible for data collection. AHA was responsible for data collection. IEEB performed critical revisions and contributed to the editing of the final manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interests regarding the publication of this manuscript.

Ethical issues: None

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