



Role of Bryophytes in Carbon Sequestration and Interactions with other Ecological Processes

Pooja Swarnkar, Shivom Singh*, Shivani Gore¹ and Kajal S. Rathore²

Department of Environmental Science,

¹Department of Biotechnology, ITM University Gwalior-474 001, India

²Department of Biotechnology, SMS Govt. Model Science College Gwalior-474 009 India

*E-mail: shivomsingh101@gmail.com

Abstract: The increase in carbon levels in the environment, especially in the form of carbon dioxide (CO₂), is largely driven by human activities such as burning fossil fuels, deforestation, and industrial processes. The rise in carbon dioxide levels has a profound environmental impact, leading to global warming, higher temperatures, melting ice caps, and an increase in extreme weather events like flooding. Areas covered by bryophytes are essential in absorbing atmospheric carbon, playing a significant role in carbon cycling, particularly in sequestration and storage within ecosystems. The ability of bryophytes to sequester carbon is shaped by various factors, including environmental conditions and their biological traits. Moreover, bryophyte communities are often more responsive to environmental changes than vascular plants, suggesting possible shifts in ecosystem structure and function. This review provides a detailed examination of the role bryophytes play in carbon cycling and their potential to mitigate climate change, highlighting their importance in the global carbon cycle and their adaptability to changing environmental conditions.

Keywords: Bryophytes, Carbon sequestration, Peat formation, Soil stabilization, Water retention

The increase in carbon levels in the environment, particularly in the form of carbon dioxide (CO₂), is largely driven by human activities such as fossil fuel combustion, deforestation, and industrial processes (Zukauskiene 2023, Kalashnikova et al., 2019, Sarkodie and Owusu 2016, Alsarhan et al., 2021, Ye et al., 2019). Fossil fuel combustion is a major contributor to rising atmospheric CO₂ levels (Kalashnikova et al., 2019), while deforestation disrupts the natural carbon cycle by reducing the Earth's capacity to absorb CO₂ (Zukauskiene 2023). Additionally, industrial activities, particularly those related to energy production and transportation, are key sources of CO₂ emissions (Kalashnikova et al., 2019, Sarkodie and Owusu 2016).

The environmental impacts of increasing CO₂ levels are significant, leading to global warming, rising temperatures, melting ice caps, and more frequent extreme weather events such as flooding (Zhang 2023). The connection between atmospheric CO₂ and Earth's temperature is well-documented, with CO₂ serving as a primary factor regulating the planet's temperature. Although the greenhouse effect of CO₂ has been understood for over a century, research continues to refine our understanding of its role in climate dynamics (Zukauskiene 2023). In response, various strategies, including carbon capture and utilization technologies, have been explored to mitigate the impact of CO₂ emissions (Zhou et al., 2015, Kadarukmi 2023, Li and He 2023).

Bryophytes, particularly mosses, are crucial for storing organic carbon in peatland ecosystems, playing a significant

role in the terrestrial carbon cycle (Weston et al., 2014). Areas covered by bryophytes are key in absorbing atmospheric carbon, with *Sphagnum* mosses being major contributors to carbon sequestration and essential players in the global carbon cycle (Silvan and Jokinen 2016). Unlike vascular plants, bryophytes lack lignin in their cell walls, resulting in a unique structural composition (Liu et al., 2018). Due to their minimal or absent cuticle, they rely on moist environments to avoid desiccation, which also enhances their capacity to absorb atmospheric contaminants (Kosonen and Meier 2021). *Sphagnum* mosses help maintain wet, oxygen-poor, and acidic conditions that slow decomposition, leading to greater organic matter accumulation and improved carbon storage in peatlands (Sytiuk et al., 2022).

Bryophytes are crucial for capturing CO₂ through photosynthesis, reducing greenhouse gas levels, and mitigating global warming. They thrive in environments where vascular plants struggle, covering forest floors, fields, and even growing on tree trunks and rocks (Shi et al., 2021, Kasimir et al., 2021). For instance, *Polytrichum* species, or haircap moss, significantly contribute to carbon sequestration by forming organic-rich soil layers in habitats like forest floors, open fields, and tundra regions (Coxson and Marsh 2001). Similarly, *Marchantia polymorpha*, or common Liverwort, aids in soil formation and stabilization, thereby enhancing carbon sequestration. Although liverworts are generally less effective than mosses in sequestering carbon, they play a vital role in increasing soil carbon content by

colonizing disturbed or bare soils, initiating ecological succession, stabilizing soil, and boosting carbon retention in environments such as forest floors, rocks, and damp soils (Bowman et al., 2017). Furthermore, bryophytes interact with other plants and respond to environmental changes, underscoring their ecological importance for carbon sequestration and nutrient cycling (Swarnkar et al., 2024). This review explores how bryophytes sequester carbon, their role in carbon storage across various ecosystems, and their potential in mitigating climate change.

BRYOPHYTES ROLE IN CARBON SEQUESTRATION

Photosynthesis and Carbon Fixation

Bryophytes, like other plants, absorb carbon dioxide from the atmosphere through photosynthesis and convert it into organic carbon compounds essential for their growth and development. Their unique photosynthetic characteristics, such as the saturation of photosynthesis at relatively low light levels, have been well-documented in scientific literature. For example, bryophytes, including mosses and liverworts, display light-response curves indicating that photosynthesis saturates at low irradiances (Marschall and Proctor 2004). Additionally, anatomical features of bryophytes, such as their

influence on non-stomatal diffusion conductance, significantly affect their photosynthetic efficiency, underscoring their adaptations to specific environmental conditions (Dangar 2024). Different bryophyte species exhibit variations in photosynthetic capacity and functional traits, with erect species allocating more nitrogen to chloroplast pigments, thereby enhancing their light-harvesting abilities compared to prostrate species (Lang et al., 2009). Bryophytes also form associations with nitrogen-fixing cyanobacteria, act as thermal insulators for the soil, and produce resistant litter. Together, these factors influence net primary productivity and heterotrophic respiration, thereby contributing to carbon fixation (Lindo et al., 2013). Their unique morphological and eco-physiological traits, such as their ability to retain moisture and withstand extreme environments, enable bryophytes to thrive in regions where most vascular plants cannot, allowing for significant carbon fixation in boreal and tropical areas (Jassey et al., 2022).

Peat Formation

Sphagnum mosses play a critical role in the biogeochemical processes of peatlands by establishing hyperacidic, waterlogged, and anoxic conditions. These environmental factors are essential for reducing the rate of organic matter decomposition and promoting the formation of peat, a key component in long-term carbon sequestration and ecosystem regulation (Healey et al., 2023, Sytiuk et al., 2022). The accumulation of peat is facilitated by the slowed breakdown of organic material, resulting in substantial carbon storage that can persist for thousands of years. Additionally, *Sphagnum*-derived phenolic compounds contribute to this carbon storage by being more resistant to microbial degradation than the litter of vascular bog plants, thereby enhancing the longevity of carbon sequestration in peatlands (Berendse et al., 2001). *Sphagnum* mosses outcompete vascular plants and microbial decomposers by promoting their own growth while suppressing others, which reduces litter decomposition and significantly contributes to the high carbon storage capacity of peat bogs (Fudyma et al., 2019). Peatlands, which hold about one-third of the Earth's soil carbon, benefit from conditions such as high acidity, nutrient-poor environments, cold temperatures, water saturation, and anoxic conditions, all of which limit decomposition (Kostka et al., 2016). Globally, peatlands store approximately 600 gigatonnes of carbon, accumulated since the last glacial maximum, making them a persistent carbon sink throughout the Holocene (Charman et al., 2012).

BRYOPHYTES ROLE IN CARBON STORAGE

Slow Decomposition Rates

The unique chemical composition of bryophyte cell walls, particularly in *Sphagnum* mosses, significantly contributes to

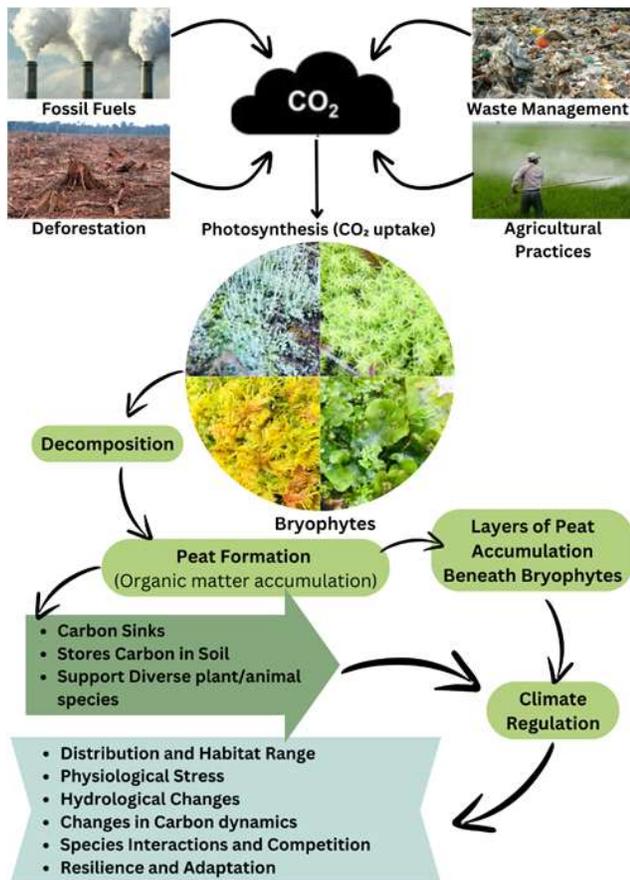


Fig. 1. Bryophyte's contribution to mitigating CO₂ emissions from various sources and climate regulation

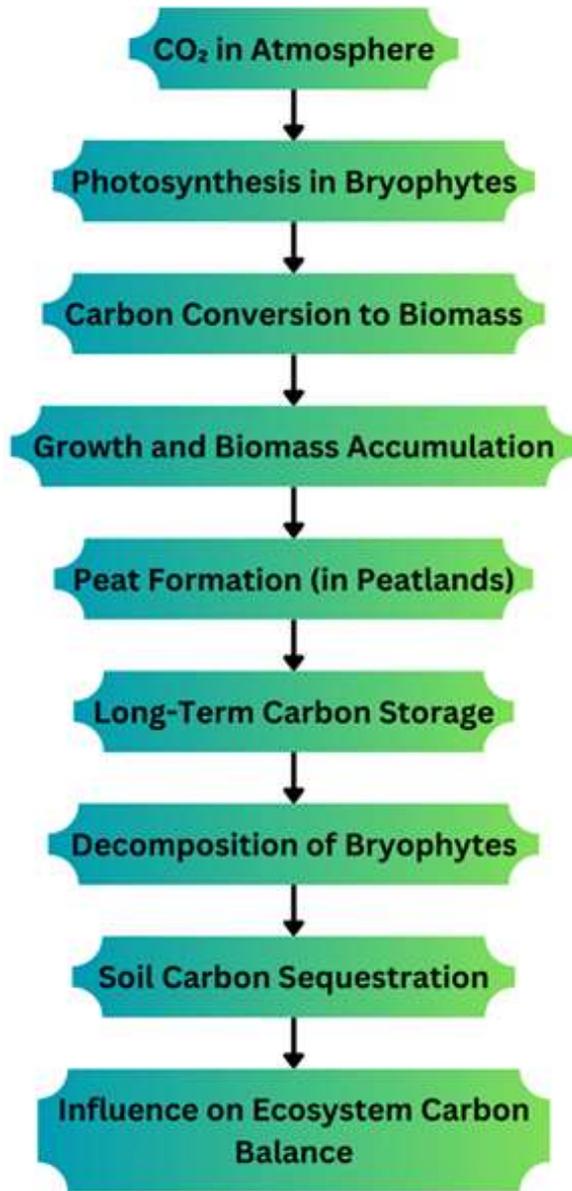


Fig. 2. Overview of the different bryophytic processes in carbon sequestration

their resistance to microbial breakdown (Hajek et al., 2010). The polysaccharides in these cell walls actively inhibit decomposition, which helps maintain the mosses' structural integrity. Additionally, high concentrations of osmolytes and the enhanced cation exchange capacity of moss cell walls increase their tolerance to environmental stressors, such as soil salinity (Lobachevska et al., 2019). In peatlands, the waterlogged conditions influence interactions between plants and microbial communities. *Sphagnum* mosses, in particular, are associated with diazotrophic methanotrophs that play essential roles in nitrogen fixation and methane oxidation, crucial processes for nutrient cycling in these ecosystems (Kox et al., 2020, Kolton et al., 2022). Peatlands

are recognized as significant carbon sinks, with the rate of carbon accumulation expected to decrease gradually over millennia due to the balance between reduced net carbon accumulation in existing peatlands and the formation of new peatlands (Gorham et al., 2012).

Carbon Storage in Biomass

Bryophytes contribute significantly to carbon storage not only through peat formation but also within their own tissues (Kiebacher et al., 2023). Their unique tissue organization differentiates them from vascular plants, leading to distinct functional traits that may not align with patterns observed in vascular plant leaves or canopies (Rice et al., 2008). The poikilohydric properties of bryophytes, which allow them to retain water in varying environmental conditions, further highlight their role in ecosystem functioning and water storage. However, climate warming poses a threat to bryophytes, potentially causing severe damage to these organisms (Oishi 2018). Additionally, bryophytes are crucial for substrate revitalization, as they can accumulate carbon and mineral nutrients, supporting ecosystem health and function (Kyyak et al., 2020).

ROLE OF BRYOPHYTES IN ECOSYSTEM DYNAMICS

Bryophytes as Bioindicators in Ecosystem

The anatomical features of bryophytes make them to accumulate heavy metals such as cadmium and lead as a function of the pollution levels at both terrestrial and aquatic ecosystems (Desai et al., 2025). Bryophytes are poikilohydric organisms that quickly react on environmental variations. Altered growth, reproduction, and tissue chemistry constitute early signs of ecological stress resulting from the exposure to pollutants (Gosselin et al., 2024). Strongly linked to pollution gradients, especially in urban and industrial areas, the species distribution of bryophyte species is strongly linked to pollution gradients (Sinha et al., 2021). This aligns with the further use of some species like *Tortella tortuosa* as targeted indicators, as they are tolerant to heavy metals (Zuijlen et al., 2024). Moreover, bryophyte communities changes can indicate nutrient enrichment and eutrophication in natural waters (Fernandez-Martinez et al., 2020). It is shown in studies on *Scopelophila cataractae*, that this adaptation allows the ability of this alga to accumulate copper in the cell wall pectin, this adaptation constitutes a response to available metal levels, but also from metal stressed conditions (Sheng et al., 2023).

The metallophyte bryophytes such as *Mielichhoferia elongata* have been observed to live in metal rich soils, indicative of the broader category of the metallophyte bryophytes that inhabit adverse environmental situations. *Fontinalis* and *Brachythecium rivulare*, an indication of certain class of environmental conditions includes the presence of

iron oxides within its habitat (Glime 2024). *Polytrichum* and *Sphagnum* have also shown the extraordinary ability to bioaccumulate various mineral such as iron (Oestmann et al., 2024). For instance, *Sphagnum* mosses can change the surrounding pH to conditions promoting the precipitation of the iron minerals (Oestmann et al., 2024).

In the particular situation with forest ecosystems, bryophytes are precious indicators of microhabitat conditions which particular inestimable flora and fauna. They are good bioindicators, because of their sensitivity to environmental changes, for assessing ecosystem health and the nature of recovery to disturbances such as deforestation or climate change (Slate et al., 2024). The first is that bryophytes greatly affect the water economy or forest ecosystems. In becoming natural water reservoirs and frequently maintaining moisture levels in the forest floor they play an impact within the hydrological cycle. For example, the ability of these bryophytes to retain water, not only helps with their propagation, but also prolongs the hydration completed by the surrounding flora. In addition, epiphytic bryophytes can improve moisture retention to extend dispersion of rainfall and fog driven water to the forest floor, which may benefit seedling survival rates, promote understory biodiversity (Desai et al., 2025). This interplay illustrates the importance of bryophytes in keeping microhabitat environments normal.

Soil Stabilization and Erosion Prevention

Bryophytes, play a crucial role in stabilizing soil and preventing erosion in various ecosystems, such as forest floors, alpine regions, and along water bodies. Research indicates that bryophyte-dominated crusts enhance water infiltration, reduce runoff, and mitigate soil erosion (Seitz et al., 2017). Mosses have been shown to reduce surface runoff by up to 91% and soil erosion by nearly 100%, while increasing percolated water by 85% compared to bare soils. In temperate forests, bryophyte covers act as protective agents against soil erosion by stabilizing soil surfaces (Gall et al., 2022). Additionally, the rhizoids of bryophytes root-like structures that anchor the plants play a critical role in binding soil particles together and interweaving with adjacent plants, forming compact cushions that are resistant to detachment from the soil. This interwoven structure of bryophytes helps trap soil particles, preventing them from being carried away by water during floods (Datta et al., 2011). In particular, bryophytes such as *Barbula unguiculata* (Pottiales) and *Bryum dichotomum* (Bryales) are stress-tolerant species commonly found in areas with abundant bare soil cover. These species are typical of ground pioneer communities that are adapted to areas with strong sea aerosols and winds, characterized by their ability to colonize challenging environments (Marignani et al., 2020). Mosses like

Ceratodon purpureus play a vital role in stabilizing extensive sand dune systems along coastlines by retaining moisture and preventing erosion. Their resilience is evident as they can survive even when covered by sand, highlighting their adaptation to harsh conditions (Moreno-Casasola 1986). In coastal dune systems, the presence of mosses such as *Ceratodon purpureus* contributes significantly to overall vegetation cover, which is crucial for stabilizing dunes and preventing their movement (Camprubi et al., 2010). Currently, mosses like *Polytrichum*, *Atrichum* and *Ceratodon* are being cultivated around fruit trees, such as apples and pears, to combat soil erosion (Groeneveld and Rochefort 2005). *Riccia* species are forming mat in terrestrial ecosystems where they apparently help to stabilize soil and control erosion as the role is still unconfirmed by any more empirical studies. This persistence under these desiccation stress conditions makes them candidate species for ecosystem restoration (Rzeczynska et al., 2022).

Water Retention and Microclimate Regulation

Bryophytes develop specialized water retention and nutrient absorption systems because their lack of vascular tissues assigns limits to their height (Rodriguez-Lopez et al., 2021). Bryophytes absorb water and nutrients directly from their environment due to their basic tissue structure. The root-like structures occurring in bryophytes called rhizoids are involved in water and nutrient absorption. Bryophytes survive in diverse environments primarily by means of capillary action, diffusion and ion exchange. The rhizoids bring about the passive movement of liquid water into the bryophyte through capillary action. The thin-walled structures maximize surface area and water contact in order to be effective absorbers. In addition to gas exchange, diffusion is important for nutrients uptake, as the minerals are diffused into rhizoid cells in concentrations gradients (Proctor and Tuba 2002). *Funaria hygrometrica* are of utmost importance for their growth under varying hydration levels, and can accommodate well to unfavorable hydration conditions only when they are in their case. Leaf shape, cell arrangement and surface modifications such as papillosity aid in water capture and minimize loss under fluctuating moisture conditions typically, unistratose leaves are the characteristic of bryophytes (Malo et al., 2025).

This water retention capability is crucial for their function and is influenced by factors such as colony structure and shoot morphology (Elumeeva et al., 2011). The water storage capacity of bryophytes varies among species and is linked to specific functional traits. For instance, deeper bryophyte layers generally exhibit a greater capacity for water storage compared to thinner layers. This enhanced water-holding capacity contributes to cooler soils and improved

temperature insulation in ecosystems where bryophytes are present (Bjorkman et al., 2019). Moss species such as *Amblystegium serpens* and *Oxyrrhynchium hians* are noted for their higher water storage capacity compared to other moss species (Thielen et al., 2021). These traits are particularly important for both bryophyte layers and biocrust bryophytes, underscoring their role in increasing water content in substrates and supporting overall ecosystem health (Slate 2024). Among the remarkable ecosystem services provided by *Riccia* species, and in particular by *Riccia fluitans*, are cyclic supply of nutrients and purification of water. *R. fluitans* is found in freshwater habitats and absorbs excess nitrogen and phosphorus to stop or limit eutrophication and improve water quality (Deilmann et al., 2024). The regulation of this nutrient supports life aquatic biodiversity by ensuring better developed aquatic habitats.

FACTORS INFLUENCING CARBON SEQUESTRATION

Species and Functional Traits

Mosses, are integral to carbon sequestration due to their unique functional traits and species-specific characteristics. Peat mosses, such as *Sphagnum* spp., are especially proficient at carbon sequestration owing to their rapid growth rates and their capacity to accumulate and preserve organic matter in peatlands (Rice et al., 2008). The functional traits of bryophytes, which are influenced by factors such as plant-soil interactions and vegetation composition, play a significant role in soil carbon sequestration amid global changes (De Deyn et al., 2008). Bryophytes form symbiotic relationships with nitrogen-fixing cyanobacteria, act as thermal insulators for the soil, and produce recalcitrant litter, all of which impact net primary productivity and heterotrophic respiration (Lindo et al., 2013). Bryophyte's presence can establish a microhabitat that allows for supporting more diverse microbial communities and interactions that thrive soil fertility. For example, bryophytes can change such processes as nitrogen fixation in soil, by their association with soil bacteria and fungi (Yang et al., 2022). Overall productivity can be improved by these microorganisms because they can improve nutrient availability to bryophytes and other surrounding vascular plants (Glime, 2024). In addition, there are some bryophytes that form symbiotic relationship with mycorrhizal fungi, so it also facilitates nutrient uptake in bryophytes and other plants around (Glime 2024). In terms of facilitating higher plant growth, bryophytes may positively influence the soil microclimate. They help regulate moisture levels, temperature, and nutrient retention through their structural features. For example, dense bryophyte cover can reduce soil erosion, maintain humidity, and mitigate temperature fluctuations, which are beneficial for the germination and establishment of vascular plant seedlings

(He et al., 2016).

Although bryophytes are often categorized into functional groups due to difficulties in species identification, this approach may obscure the contributions of individual species to carbon sequestration (Lett et al., 2021). Research indicates that intraspecific variation is significant for vascular plants and lichens, while species turnover is a primary driver of trait variation in bryophytes (Zuijlen et al., 2021). Functional trait diversity is a crucial determinant of soil organic carbon sequestration across different successional trajectories (Satdichanh et al., 2023).

Water Availability

To understand the impact of drought conditions on carbon sequestration in bryophytes, it is essential to examine their reliance on water for physiological processes, growth, and photosynthesis. Bryophytes, including mosses, exhibit a range of water retention traits crucial for their adaptation and survival across different habitats (Proctor and Tuba 2002). Size, shape and aggregation of shoot morphology are of paramount importance in desiccation tolerance (DT), because of a microclimate effect granting an advantageous microclimate, which decreases the dehydration rates (Noualhaguet et al., 2023). Trapping and retaining water are one of these cushion forming colonie's pretenions to the drought or other sudden environmental changes (Elumeeva et al., 2011). Additionally, the motion of bryophytes to environmental cues, for example, leaf reorientation and shape change depending on the light intensity, allows to promote photosynthetic efficiency while minimising water loss (Kuttim et al., 2019).

Some examples of bryophyte species are mentioned below.

1. *Sphagnum palustre* are highly adapted for water retention, and what allows them to survive in saturated environments (Oestmann et al., 2024).
2. Such species as *Polytrichum commune* use their large number of rhizoids to attach to organic substratum and even to take out the moisture from ephemeral water sources to survive in different habitats (Botroh et al., 2023).
3. Thalloid form of *Marchantia polymorpha* can absorb water directly and allow gas exchange across its surface and is well adapted to moist habitats (Noualhaguet et al., 2023).
4. *Bryum argenteum* form colonies can be extensive, important in trapping moisture, and have ecological functions (Deilmann et al., 2024).
5. Those species such as *Isopterygium muelleri* that grow in shady locations have larger leaves for tapping as much light as possible (Rzeczczynska et al., 2022).

6. *Riccia fluitans* is known to modify its morphology in response to water levels and light intensity, and it often resides in temporary water bodies, where its survival is enabled through changes of morphology (Wang et al., 2022).
7. Furthermore, bryophytes play a role in regulating nitrogen inputs in boreal forests, which can impact forest productivity and the overall carbon sequestration response to environmental changes (Gundale et al., 2011). The water balance of bryophytes, influenced by factors such as colony structure and shoot morphology, is crucial for their habitat selection and physiological functions. This highlights the complex interplay between water availability and bryophyte ecology (Elumeeva et al., 2011).

Temperature

Temperature exerts a profound influence on bryophyte metabolism, growth rates, and the decomposition of organic matter, all of which impact their carbon sequestration capacity. Optimal temperature ranges facilitate higher growth rates and enhanced carbon sequestration in bryophytes, whereas extreme temperatures—both high and low—can stress these organisms and diminish their effectiveness in carbon sequestration (Rzeczynska et al., 2022). The temperature is a pivotal factor in shaping the carbon sequestration capacity of ecosystems. For instance, in the *Picea schrenkiana* forests of the Tianshan Mountains, China, temperature variations account for a significant portion of long-term changes in carbon sequestration capacity, with minimum temperatures playing a particularly critical role (Zhou et al., 2021). Bryophytes exhibit diverse responses to temperature fluctuations, with different species demonstrating variable growth and nitrogen fixation rates in response to temperature changes (Rzeczynska et al., 2022). Additionally, bryophytes are essential in regulating soil surface temperature and humidity, influencing organic matter decomposition, and fixing atmospheric carbon through photosynthesis, which contributes to carbon deposition in the soil. This underscores the complex relationship between temperature, bryophyte ecology, and carbon dynamics (Chen et al., 2022). Extreme temperatures, including those encountered during droughts or winter cold stress, can profoundly affect bryophyte physiology and carbon sequestration processes. During winter, when temperatures approach or fall below freezing, bryophytes experience cold stress that impairs their metabolic activities and growth (Peters et al., 2019). Temperature fluctuations can also modify soil temperature regimes, thereby influencing soil carbon and nutrient turnover. In Polar Regions, where bryophytes are pivotal in regulating soil temperature, these

temperature changes can significantly impact ecosystem dynamics (Soudzilovskaia et al., 2013).

Light Availability

Light availability is a crucial determinant of the photosynthetic capacity, growth, and carbon capture of bryophytes. As photosynthetic organisms, bryophytes depend on light for energy production. In shaded environments, their photosynthetic efficiency can be limited, while areas with adequate light promote robust growth and enhanced carbon sequestration (Niinemets 2010). The availability of light is essential in shaping bryophyte communities, affecting species occurrence and abundance (Dyderski and Jagodzinski 2020). The light availability directly impacts the photosynthetic activity of bryophytes, with different species demonstrating varied responses to light intensity (Wang et al., 2015). Bryophytes exhibit specific structural adaptations to environmental conditions, including light intensity and water availability, which influence their photosynthetic capacity and growth patterns (Wang et al., 2015). Furthermore, light availability not only affects photosynthesis but also has indirect effects on moisture levels and humidity within forest ecosystems, which in turn impacts bryophyte physiology and broader ecosystem processes (Shao et al., 2023).

Nutrient Availability

Nutrient levels in soil and water have a significant impact on bryophyte growth. While some bryophytes are well-adapted to nutrient-poor environments, others benefit from moderate nutrient availability, which can enhance their growth and carbon sequestration potential. Bryophytes also play a crucial role in influencing soil nutrient availability through various mechanisms. For example, Koranda and Michelsen (2020) examined how bryophytes affect microbial decomposition processes and soil nutrient availability in a subarctic birch forest. The dead biomass of bryophytes provides to the organic matter pool and hence microbial growth and nutrient availability of surrounding plants. Hence, relatedly, there are bryophytes, including *Hylocomium splendens*, that can slow soil nutrient turnover due to their acidic litter, which alters the interactions of soil microbial communities with soil nutrients (Yang et al., 2022). Their study underscores the importance of bryophytes in regulating soil nutrient dynamics and supporting overall ecosystem function.

pH and Soil Conditions

Soils with more acidic pH levels and lower macronutrient concentrations generally support greater bryophyte coverage (Rola et al., 2021). In Hemiboreal Scots pine forests in Estonia, soil pH at the studied sites ranged from 2.1 to 3.3, reflecting highly acidic conditions. Consequently, sites

with higher pH levels tend to exhibit greater plant group richness, consistent with findings from previous research (Orumaa et al., 2022). Additionally, an increase in soil carbon, nitrogen, and organic matter content, coupled with a lower pH, has been linked to the establishment of bryophyte cover (Ortiz et al., 2023). *Hylocomium splendens*, a dominant boreal forest moss, pulls water soluble nutrients from the soil and accumulates rich, nitrate rich, organic matter of low pH. The moss's capacity to take up mineral nutrients from the environment, plus the decomposition that is derived from it, primarily contributes to soil acidity, which is this natural process more enhanced (Jaroszynska et al., 2023). More specifically, *Sphagnum* species are known for having cation exchange processes wherein proton release occurs into the soil which then decreases the pH (Oestmann et al., 2024). Soils and land managed by bryophytes have tended to accumulate organic matter in the form of soil organic carbon. The study specifically highlights that higher density of biomass of bryophyte species augments soil organic matter accumulation. In particular, bryophyte species differ in the degree to which they are capable of coping with different moisture and nutrient conditions, which improve their overall contribution to content of soil organic carbon (Rainford et al., 2022).

Disturbance and Land Use Changes

Disturbances and land use changes have a profound impact on bryophyte communities and their diversity. Research indicates that disturbances, such as treefall, can enhance bryophyte diversity in boreal forests by creating new colonization opportunities, increasing habitat heterogeneity, and facilitating the establishment of bryophyte diaspores (Jonsson and Esseen 1990). Conversely, land use changes, particularly intensified agricultural practices, can adversely affect bryophytes. For instance, Muller et al. (2012) demonstrated that fertilizer application promotes the growth of vascular plants, which compete with and suppress bryophyte populations. Fertilizers can significantly reduce bryophyte species richness, as many bryophyte species are intolerant of high nitrogen levels, which favor the growth of taller grasses and herbs and increase light competition on the forest floor. Additionally, nutrient enrichment from agricultural runoff further disrupts bryophyte habitats, posing a major threat to their communities. Hejcman et al. (2009) observed that long-term fertilizer uses results in a negative correlation between the biomass of vascular plants and bryophytes in grassland ecosystems. This suggests that increased nutrient levels favor vascular plants at the expense of bryophytes. Intensified land use can exacerbate this trend by decreasing bryophyte diversity through multiple mechanisms. These include direct mechanical impacts such as grazing and

mowing, toxic effects from high nitrogen applications, and indirect effects from increased productivity that intensify competition from taller plant species (Muller et al., 2012).

Diversity and Composition of Bryophytes

The diversity and composition of bryophyte communities have a profound impact on their overall carbon sequestration capacity. Diverse bryophyte communities often exhibit complementary traits that enhance ecosystem functioning and carbon storage. The variety and composition of bryophyte species are crucial for carbon assimilation and productivity on the forest floor (DeLucia et al., 2003). Environmental factors, such as soil drainage, significantly influence bryophyte distribution and net primary productivity (NPP) (Bisbee et al., 2001). Bryophytes affect organic matter decomposition by regulating soil surface temperature and humidity, carbon fixation via photosynthesis, and carbon deposition in the soil (Chen et al., 2022).

Particularly, *Sphagnum* mosses are key ecosystem engineers in northern peatlands, where they store substantial amounts of carbon (Rice et al., 2008). These mosses form associations with nitrogen-fixing cyanobacteria, act as thermal insulators for the soil, and produce recalcitrant litter, all of which impact net primary productivity and heterotrophic respiration (Lindo et al., 2013). Additionally, the colonization of bryophytes is influenced by the diversity and composition of vascular plant species, highlighting the intricate interactions between different plant groups (Fergus et al., 2017). The factors affecting carbon sequestration in bryophytes are interconnected, involving a combination of biological interactions, environmental conditions, and land management practices.

IMPACTS OF CHANGING CLIMATE ON BRYOPHYTES

Bryophyte communities have been found to be more responsive to environmental changes than vascular plants, suggesting potential shifts in ecosystem structure and function (Post and Pedersen 2008, Oishi 2018).

Changes in Distribution and Habitat Range

As temperatures rise due to climate change, bryophytes are projected to shift their ranges towards higher elevations or poleward locations. Research shows that bryophyte diversity and distribution are influenced by elevation, temperature, and precipitation. This range shift could lead to a reduction in suitable habitats, particularly for species specialized to specific climates or microhabitats (Sun et al., 2013, Marschall 2017, Coelho et al., 2023). Warming temperatures and altered precipitation patterns present significant threats to bryophyte habitats, especially in alpine regions, boreal forests, and peatlands, where they play critical ecological roles. Studies have demonstrated that bryophyte cover and richness can decline in response to

experimental warming, with noticeable reductions observed in many species in Alpine Sweden (Sun et al., 2013).

Physiological Stress

Bryophytes, owing to their poikilohydric nature, are particularly sensitive to temperature changes because they cannot independently regulate their internal water content. This sensitivity heightens their vulnerability to desiccation and diminished photosynthetic activity under elevated temperatures. Additionally, the increase in UV-B radiation associated with climate change poses further risks to bryophytes by affecting their growth and reproduction. Due to their lack of protective cuticle layers and differentiated leaves, bryophytes are especially susceptible to UV-B radiation. Such exposure can cause DNA damage and physiological disturbances, exacerbating stress under increased UV-B conditions (Oishi 2018, Soudzilovskaia et al., 2013, Lappalainen et al., 2007). Some bryophytes, like *Bryum argenteum*, and *Marchantia polymorpha* have gone to great lengths to deal with dehydration. Gao et al. (2017) showed that desiccation tolerant bryophytes mount a successful recovery response to dehydration following transcriptional and translational controls, including the accumulation of specific proteins that stabilize cellular structures and metabolic processes during and after dehydration. Similarly, *Marchantia polymorpha* have the potential to osmoregulate during salt stress conditions where, it lacks specialized physiological mechanism halophytes and still maintain cell turgor and osmosis balance by effective water retention strategies (Lobachevska et al., 2019). It takes place by osmoregulation with accumulation of osmoprotectants such as proline, reducing osmotic potential and protection of cells. According to Ghosh et al. (2021) *Physcomitrella patens* and *Marchantia polymorpha* both respond to drought conditions with increased ABA levels correlating with increased stress resilience. For bryophytes, this adaptation is critical because the soil moisture and availability of water is highly variable.

Hydrological Changes

Changes in precipitation patterns, including increased drought frequency and alterations in snowmelt timing, can significantly impact bryophytes, which rely heavily on surface water for hydration. Reduced water availability may lead to decreased growth and potential mortality in certain bryophyte species. Despite their desiccation tolerance mechanisms, where cells can transition between full turgidity and desiccation to suspend metabolism during water scarcity (Proctor and Tuba 2002, Marschall 2017) bryophytes remain highly dependent on external water sources. Their water content diminishes rapidly with rising temperatures and decreased humidity (Oishi, 2018). Unlike vascular plants,

bryophytes absorb water directly through their stems and leaves from rain, fog, or dew, highlighting their reliance on atmospheric precipitation (Coelho et al., 2023, Song et al., 2021). Peatlands, particularly in the northern hemisphere, act as crucial carbon sinks but face significant challenges due to climate change-induced factors such as warming temperatures and increased drought frequency. These conditions contribute to gradual drying and extreme weather events, which can adversely affect peatland ecosystem functions and diminish their carbon storage capacity (Kang et al., 2018, Yan et al., 2022, Koster 2023).

Changes in Carbon Dynamics

In peatlands and other ecosystems dominated by bryophytes, the impacts of climate change are deeply interconnected. Warming temperatures can accelerate decomposition processes in peatlands, potentially releasing significant amounts of stored carbon and further exacerbating climate change. As critical carbon sinks, peatlands are increasingly vulnerable to climate change-related factors such as rising temperatures and prolonged droughts, which can severely impair their capacity to function as carbon reservoirs (Larmola et al., 2014, Norby et al., 2019).

Bryophytes play a crucial role in these dynamics. In boreal forests, they help mitigate the effects of anthropogenic nitrogen inputs, which can otherwise create detrimental feedback loops in carbon cycling. Variations in bryophyte biomass influence soil temperatures, which in turn affect carbon mineralization rates and carbon sequestration in soils (Gundale et al., 2011). For instance, increased bryophyte biomass can provide insulation to the soil, thereby slowing decomposition processes and enhancing carbon storage. Moreover, the contribution of bryophytes to ecosystem CO₂ exchange is highly sensitive to rapid climate changes due to their reliance on water availability and the depth of the water table (DeLucia et al., 2003). Alterations in hydrological cycles induced by climate change can significantly impact bryophytes' ability to regulate CO₂ exchange. As ecosystems globally adapt to climate changes, the distribution of bryophyte-influenced biomes is anticipated to shift, which will, in turn, influence their contributions to global ecosystem functions (Slate 2024). The changing distribution and functionality of bryophytes across various ecosystems will be a crucial factor in future carbon dynamics and the overall health of these ecosystems.

Species Interactions and Competition

Climate change, exacerbated by factors such as pollution and habitat loss, intensifies the threats posed to bryophytes by invasive species (Lianah et al., 2021). Shifts in climate conditions can create more favorable environments for

invasive species, thereby increasing pressure on native bryophytes (Soudzilovskaia et al., 2013). Invasive species often assert dominance through mechanisms such as competition and displacement (Cheng et al., 2008). Research has shown that invasive species can negatively impact native bryophyte communities. For example, invasive species can impede the germination of native species in grassland remnants where bryophyte mats obstruct their establishment (Morgan 2006). Moreover, the spread of invasive species can alter the abundance and diversity of native bryophytes, thereby affecting overall ecosystem dynamics (Marignani et al., 2020). Species diversity of bryophytes may increase interactions within microbial community increasing substrates for microbial activity which is needed for the decomposition of organic substances and stabilization of SOC (Rainford et al., 2022).

Climate-induced changes in ecosystem structure and function can significantly influence the role of bryophytes within these systems, affecting their interactions with vascular plants, fungi, and microorganisms. These interactions are crucial for nutrient uptake and cycling. Climate changes, such as elevated CO₂ levels and warming, can impact these interactions, potentially altering nutrient availability and plant growth (Compant et al., 2010).

Resilience and Adaptation

Some bryophyte species may exhibit physiological or genetic changes in response to climate change, potentially allowing them to adapt to new environmental conditions. However, the rate and extent of these adaptations are likely to vary among species and ecosystems, reflecting the diverse ecological niches occupied by bryophytes (Slate 2024). For example, intercontinental gene flow and shared ancestral polymorphism have been identified as factors shaping the genetic structure of bryophyte populations, highlighting the complex dynamics of adaptation in these organisms (Szovenyi et al., 2008). Bryophytes, due to their sensitivity to environmental conditions, can benefit from microhabitats that offer more stable temperatures and moisture levels. Microhabitats such as tree hollows and leaf litter have been identified as crucial refuges that can help mitigate the impacts of extreme climate events on bryophyte communities (Keppel et al., 2017). These refuges provide essential conditions that support bryophyte persistence amidst changing climates

CONCLUSION

The bryophytes play a crucial role in carbon cycling and climate change mitigation, acting as natural carbon sinks through their ability to sequester and store carbon in ecosystems. Their responsiveness to environmental

changes, coupled with their widespread presence in various habitats, underscores their significance in the global carbon cycle. As climate change progresses, understanding and harnessing the carbon-sequestering potential of bryophytes will be essential for future conservation and ecosystem management strategies. Future advancements in this field could include more refined models of bryophyte carbon dynamics, increased focus on their restoration in degraded ecosystems, and deeper exploration of their interactions with other ecological processes. These advancements hold promise for enhancing our ability to mitigate climate change and sustain ecosystem health in a rapidly changing world.

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