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REVIEW ARTICLE

Moss control and prevention in terrestrial ecosystems: A review of chemical, biological, physical, and ecological management strategies

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Abstract

As a key component of terrestrial ecosystems, moss plays a significant role in soil and water conservation and in the regulation of the carbon cycle. However, in certain scenarios, such as container seedling cultivation, golf courses, and ecologically sensitive areas, its overgrowth can interfere with the growth of target plants, thereby disrupting ecological balance and affecting landscape functions. Additionally, moss growth in some areas influenced by human activity can make roads slippery, posing a safety hazard to pedestrians. Therefore, the suppression and prevention of moss have become a research hotspot in related fields. At present, a systematic review of governance strategies is needed for moss management. This review systematically summarizes the mechanisms, application scenarios, and research progress of moss control and prevention from four dimensions—chemical inhibition, biological control, physical regulation, and ecological management—based on the biological properties of moss, especially considering that mosses have evolved strong adaptability to diverse regional natural and climatic conditions, which necessitates region-specific control strategies, so as to provide guidance for the scientific management of moss.

Keywords: Moss control; Moss prevention; Chemical inhibition; Biological control; Physical control; Ecological management

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1. Ecological properties of mosses and management contexts

Mosses (*Bryophyta*), as a primitive group within the kingdom Plantae, are classified as non-vascular plants. They are small, terrestrial plants lacking lignified conducting tissues and reproducing by spores. Mosses form a monophyletic clade and are one of the earliest colonizers of land. From a taxonomic perspective, according to the classification framework outlined in *Introduction to Bryophytes*,[1] mosses are divided into eight primary classes that reflect their evolutionary diversification: Bryopsida, Takakiopsida, Sphagnopsida, Andreaeopsida, Andreaeobryopsida, Oedipodiopsida, Polytrichopsida, and Tetraphidopsida.

According to the latest plastid genome phylogenetic studies, mosses can be classified into 45 orders and 142 families, with the majority of species diversity concentrated within the class Bryopsida. Mosses represent one of the most species-diverse and ecologically dominant groups within bryophytes, with approximately 12,000–15,000 formally described species worldwide. Mosses exhibit a unique life cycle characterized by a dominant haploid gametophyte generation. Neither the gametophyte nor the sporophyte possesses lignified water-conducting cells, a feature that distinguishes them significantly from vascular plants. As a cosmopolitan group, mosses occupy diverse environments, ranging from tropical rainforests and temperate grasslands to polar and high-altitude extreme habitats, as well as from tidal wetlands and peatlands to human-modified landscapes. With their remarkable environmental adaptability, they have successfully colonized a wide range of habitats and play a crucial ecological role in terrestrial ecosystems, including soil and water conservation, carbon cycle regulation, and microhabitat construction.[1]

Moss has both important ecological functions and potential hazards, showing a significant duality. Ecologically, it makes significant contributions to soil and water conservation, regulates the carbon cycle, and provides microhabitats for small organisms, serving as an important carrier of biodiversity.[1] In northern peatlands, moss removal can suppress methane emissions, whereas in polar or high-altitude regions, its strong environmental adaptability makes moss the core of the ecosystem.[2] However, the harm is also prominent when moss overgrows or grows inappropriately. For the ecological environment, moss competes with target plants for light,[3] nutrients, and space, inhibits the growth of seedlings and lawn grass, spoils the landscape function, and hinders the germination and survival of vascular plant seeds in calcareous grasslands.[4] For human activities, moss on shady steps and mountain scenic road surfaces makes the ground slippery, increasing the risk of pedestrians slipping and getting injured, and posing a threat to public travel safety. While management measures are required to curb the excessive growth of moss, it is equally critical to recognize that improper implementation of such control measures may give rise to considerable environmental risks. Specifically, the indiscriminate application of chemical agents (e.g., high-concentration copper formulations[5]) can contaminate soil and surface water bodies and cause phytotoxicity to non-target plants; the complete removal of moss in natural habitats (e.g., peatlands, subarctic heathlands, and high-altitude ecosystems) reduces soil water retention capacity;[2] and excessive physical intervention can increase bare soil coverage, thereby elevating the risk of soil erosion.[6]

Therefore, the core of moss management is to clearly define the line between "the good and the evil," distinguishing when control measures merely target excessive moss growth and when they may cause environmental harm. Instead of pursuing complete removal, moss management essentially emphasizes scientific suppression, with the control goal shifted from "zero coverage" to "balancing function and risk." Specifically, moss control methods must take into account the natural and climatic characteristics of the target areas, for example, by adjusting the timing of chemical application based on polar cold resistance.[7] Reasonable measures should be adopted to curb the overgrowth and spread of moss in human-dominated scenarios such as seedling cultivation, sports fields, and walkways, thus avoiding safety risks.[8] Meanwhile, moss, as a key component of natural ecosystems, should be retained to preserve its irreplaceable ecological functions. This approach achieves the coordinated development of ecological protection and human needs, ensuring that moss management does not harm the broader environment beyond addressing targeted moss overgrowth.

2. Overview of moss control and prevention strategies

Moss control and prevention strategies can be broadly classified into four complementary approaches: chemical inhibition, biological control, physical regulation, and ecological management. Chemical inhibition uses synthetic or natural chemical agents to directly disrupt moss physiological processes, providing rapid and efficient suppression but requiring careful consideration of phytotoxicity, resistance development, and environmental safety.[9] Biological control relies on pathogenic microorganisms or bioactive compounds derived from mosses or other organisms to selectively inhibit target species, offering high ecological safety but still facing challenges in field stability and large-scale application.[10] Physical control includes mechanical removal and microenvironmental regulation (e.g., moisture, temperature, and substrate conditions) to reduce habitat suitability for mosses, typically with low pollution risk but often limited by labor costs and site specificity.[11] Ecological management adopts an integrated, long-term perspective, regulating species competition and habitat functions and combining multiple techniques in a scenario-based approach to balance moss suppression with the maintenance of ecosystem structure, biodiversity, and key ecological services.[12]

3. Chemical inhibition techniques

Chemical inhibition involves the application of chemical agents that use their chemical properties to disrupt the physiological structure of moss and inactivate it. This method is typically used in scenarios where high moss removal efficiency is required, such as large-scale moss control. Chemical control is highly effective and remains a common method for moss suppression. The applicable agents and their effects vary in different scenarios, and a balance must be considered in terms of control efficacy, environmental safety, and pesticide damage risk. Relevant studies have clarified the action characteristics and application strategies of various agents.[3,5,8,9,10,13,14] Figure 1 outlines scenario-specific chemical agents, their mechanisms, and limitations.

3.1. Screening and application of chemical agents in different scenarios

Quinoclamine can be used to control *Marchantia polymorpha* and *Polytrichum commune* in container seedling cultivation. At a concentration of 0.9 g/L, control rates of 100% and 95.5% can be achieved for the two species, respectively. Wood vinegar, flumioxazin, and oxyfluorfen also exhibit moderate control effects, but at high concentrations, they may cause damage to seedlings.[3] Herbicides such as diuron and chlorbromuron exhibit inhibitory effects on moss in container systems. Notably, the combination of ferrous sulfate and Ronstar can significantly enhance control efficacy while mitigating the risk of phytotoxicity to seedlings.[9] According to Kim *et al.*,[3] quinoclamine at 0.3–0.6 g/L provides optimal control of these mosses and is safer for seedlings than flumioxazin or oxyfluorfen. Therefore, quinoclamine is an ideal choice for moss control in container seedling cultivation, considering both removal efficiency and seedling safety.

In addition, golf courses are also key areas that require moss treatment. Silvery threadmoss is the most harmful moss species on a golf course putting green. A herbicide called carfentrazone, applied every three weeks during the growing season, can control up to 75% of the moss population. Additionally, studies have found that a variety of herbicides, including sulfentrazone, saflufenacil, and flumioxazin, achieve considerable control effects (more than 70%) before and after germination, with sulfentrazone having a much lower single application cost than carfentrazone, demonstrating its potential for application.[10] Silver nitrate, at a dose of 0.275 lb/1,000 ft^2, can completely eliminate moss after 1–2 applications with almost no phytotoxicity to lawns, but is not currently registered as a pesticide. Copper-based formulations, such as a combination of copper hydroxide and mancozeb, when applied every two weeks in autumn at a dose of 0.2 lb/1,000 ft^2, can achieve continuous control with a lower risk of pesticide damage.[5] Carfentrazone can not only effectively control silvery threadmoss but also inhibit the development of its spores and bulbils, reducing green coverage by more than 80% within three weeks. The inhibitory effects of sulfentrazone, oxyfluorfen, and other agents on moss propagules are comparable to those of carfentrazone and can be used as alternative agents to reduce the risk of resistance developing to a single agent.[10]

Mercurous chloride, as a lawn moss control agent, can effectively inhibit the germination of moss spores and the growth of vegetative bodies, and a single application can maintain the control effect for an entire growing season.[8] Among the new environmentally friendly agents,

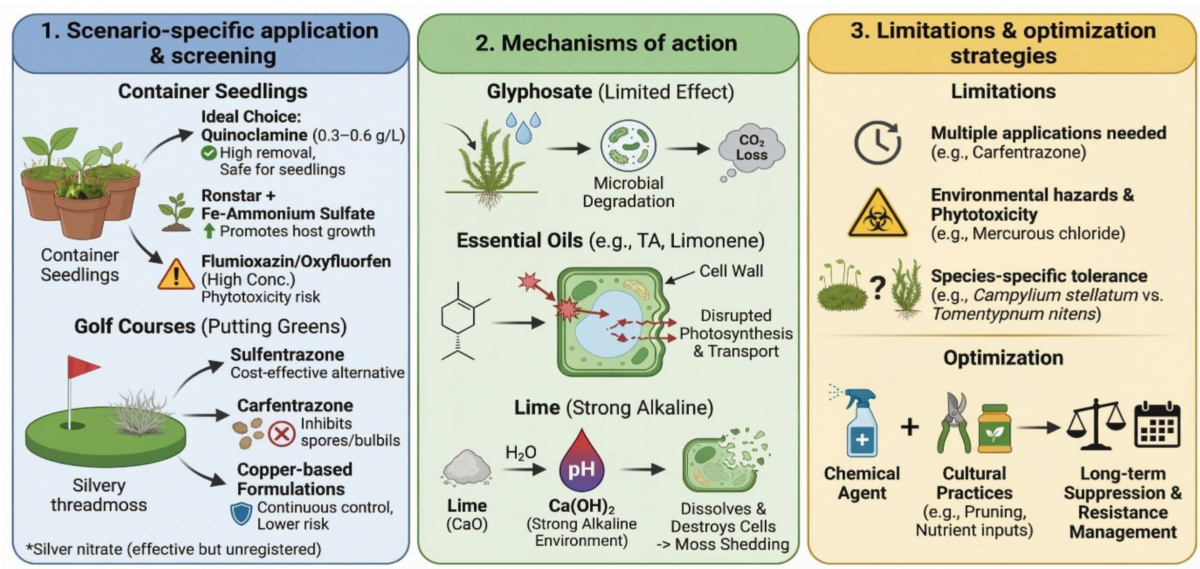

Figure 1. Chemical inhibition techniques for moss control across application scenarios. Image generated by Gemini Pro and revised by the authors. Abbreviations: CaO: Calcium oxide; $Ca(OH)_2$: Calcium hydroxide; CO_2: Carbon dioxide; H_2O: Water; Fe: Iron; TA: Terpinyl acetate.

plant essential oils and their derivatives have become a research hotspot. Terpinyl acetate, limonene, and Hinoki essential oil have stable control effects on *M. polymorpha* and *P. commune*, and can reduce cell damage to seedlings when used in combination with surfactants.[13] The herbicide Asulox, whose active ingredient is asulam, has inhibitory effects on 18 moss species, but the sensitivity varies significantly among different moss species, with *P. commune* being the most sensitive and *Warnstorfia fluitans* being the most tolerant; the ability of mosses to produce lateral branches is positively correlated with their tolerance to Asulox.[14]

3.2. Mechanism of action and application optimization of chemical agents

Absorption and transport studies of 14C-labeled glyphosate show that mosses rapidly absorb the herbicide through capillary water and reach equilibrium within one day, but the herbicide is subsequently lost in the form of CO_2 through microbial degradation, which is an important reason why some herbicides have limited control effects on mosses.[10] Terpinyl acetate and limonene cause mosses to deform their cell walls and expand intercellular spaces, disrupting their photosynthetic and nutrient transport systems.[13] The moss-removing solution, whose active ingredient is lime, can dissolve and kill moss covering the trunks and branches of tea plants by creating a strongly alkaline environment when applied via foliar and stem spraying. Moss impedes the emergence of new shoots, and this solution can cause various types of moss to shed within 3–7 days after application, eliminating the physical obstruction and interference with new shoot growth, thereby creating an unobstructed environment for shoot development.[15]

The application method significantly affects the efficacy of the agent. For example, on golf course greens, azole can be applied up to four times a year. After the application of agents such as sulfuron in spring, the competitiveness of creeping bentgrass can be enhanced in autumn through measures such as pruning vegetation and increasing nutrient input, which can suppress the growth of silver line moss over an extended period.[10]

3.3. Limitations on the application of chemical agents

Most chemical agents need to be applied multiple times to maintain their effectiveness, such as up to four times a year for the application of carfentrazone. Although silver nitrate and high-concentration copper preparations are highly effective, they pose environmental hazards and incur high costs.[5] Traditional chemical agents such as mercurous chloride, although long-lasting, also pose significant environmental hazards.[8] Additionally, some agents may affect non-target organisms and require supplementary approaches, such as biocontrol bacteria, to reduce the dosage.[16] Furthermore, there are species differences in the tolerance of mosses to chemical agents. For example, *Campylium stellatum* can maintain reproductive capacity under salt stress, while *Tomentypnum nitens* has significantly reduced reproductive capacity under submerged conditions. The species-specific tolerance complicates control efforts.[11]

4. Biological control techniques for mosses

Biological control has attracted significant attention due to its environmental friendliness. Studies have identified a variety of microorganisms that are pathogenic to moss and have found that the interaction mechanism between moss and microorganisms can provide targets for biological suppression.[10,17,18] Although research on biological control is in a transitional stage, it has shown considerable potential for application.[10] Figure 2 presents biological control: pathogenic microbes, *KP4* gene targets, eco-friendliness, and challenges.

4.1. Exploration and application of biocontrol microorganisms

Silvery threadmoss is the main harmful moss on creeping bentgrass greens.[17] Biological agents (e.g., *Alternaria solani*) can be used, and lawn competitiveness can be enhanced by increasing the mowing height and optimizing nutrient input. The combination of multiple methods can achieve efficient moss control and ensure the quality of the green. *A. solani* and *Sclerotium rolfsii*, isolated from golf course greens, may be effective species for control because they can reduce moss coverage on greens to less than 20% within 14 days.[10] Moss extracts also show potential for indirect control. Extracts from *Bazzania trilobata* inhibit plant pathogens, indirectly improving the growth environment of target plants and enhancing their competitiveness relative to mosses.[18]

4.2. Molecular mechanisms and species specificity of biological control

The proteolytic gene *KP4*, isolated from moss, regulates the calcium signaling pathway, and the protein encoded by it can cause cell death or growth defects in moss filament cells by affecting cytoplasmic calcium concentration,[18] providing molecular targets for the development of targeted biologics.

The host specificity of biocontrol microorganisms is critical to ensuring control effectiveness and ecological

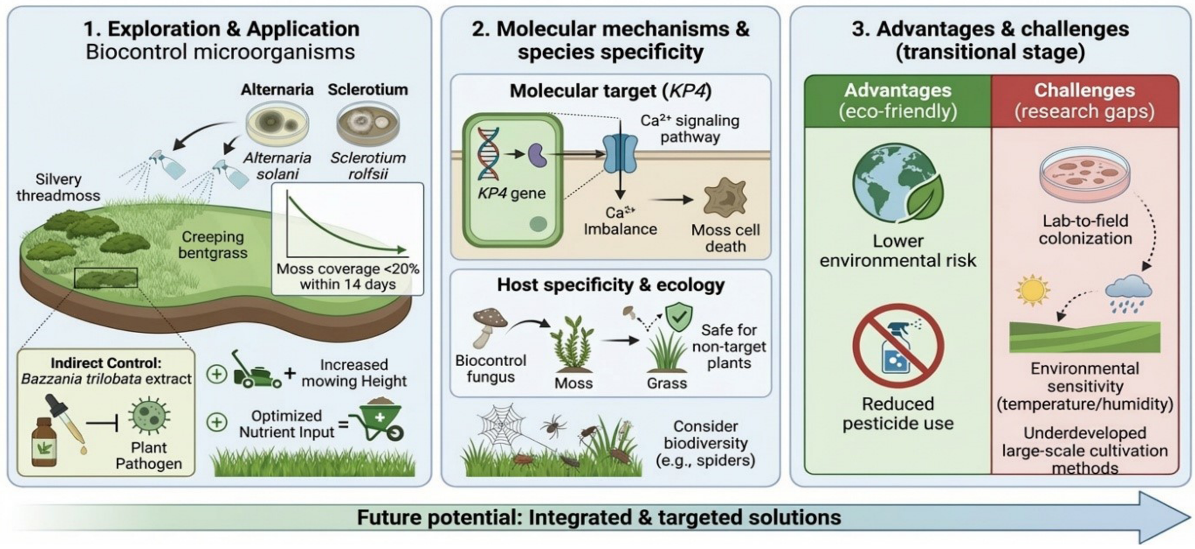

Figure 2. Biological control techniques for mosses, illustrating the mechanisms, applications, and challenges. Image generated by Gemini Pro and revised by the authors.

security. For instance, *A. solani* has no pathogenicity to the target lawn grass and is suitable for scenarios such as golf courses.[10] In grassland ecosystems, the presence of moss can alter the habitat structure of arthropods such as spiders, and the species composition and functional diversity of spiders change significantly after moss removal. Therefore, biological control schemes need to take into account the biodiversity conservation requirements of the target scenarios to avoid triggering cascading ecological effects.[6]

4.3. Advantages and challenges of biological control

Biological control can reduce the use of pesticides and lower environmental risks, but the relevant research is still at the laboratory stage. The field colonization ability, environmental adaptability, and large-scale cultivation techniques of biocontrol microorganisms are not yet mature, and their control effects are easily affected by environmental factors such as temperature and humidity.[10]

5. Physical control techniques of mosses

Physical regulation, which achieves moss inhibition through direct mechanical intervention or modification of the microenvironment, has the advantages of high efficiency and no chemical residue and is applicable to ecologically sensitive areas. However, the technology selection and effects vary across different ecosystems.[12,19,20] Figure 3 summarizes physical control: mechanical removal, microenvironment regulation, strengths, and drawbacks.

5.1. Mechanical removal techniques

Mechanical removal is the most direct physical control method, and its effect varies depending on the application scenario. Mechanical sod-and-moss removal in degraded eutrophic peatlands can effectively inhibit the growth of invasive peat moss species (e.g., *Sphagnum flexuosum*) and gradually increase the richness and abundance of the target moss species after one and a half years, facilitating the restoration of the ecosystem to the native eutrophic peatland stage. However, this measure needs to be repeated every 10 years to cope with the rapid regeneration rate of peat moss at 5–6 cm per year.[12]

In lawn and sports field turf management, artificial removal of moss can temporarily reduce its coverage locally, but it should be used in combination with chemical treatment to avoid secondary infection caused by scattered moss tissue.[8] In container seedling scenarios, manually removing moss from the substrate surface, in combination with substrate covering, can reduce the probability of reinfection.[19] In heathland ecosystems, high-intensity management with mechanical scarification can reduce nitrogen accumulation and increase bare soil coverage to inhibit moss re-invasion.[6] In subtropical forests, artificial removal of live moss significantly promotes the decomposition of wood residues and litter, increasing wood residue mass loss by 6.28–14.74% and net nitrogen loss by 6.8–16.4%.[20] While the short-term effect of direct

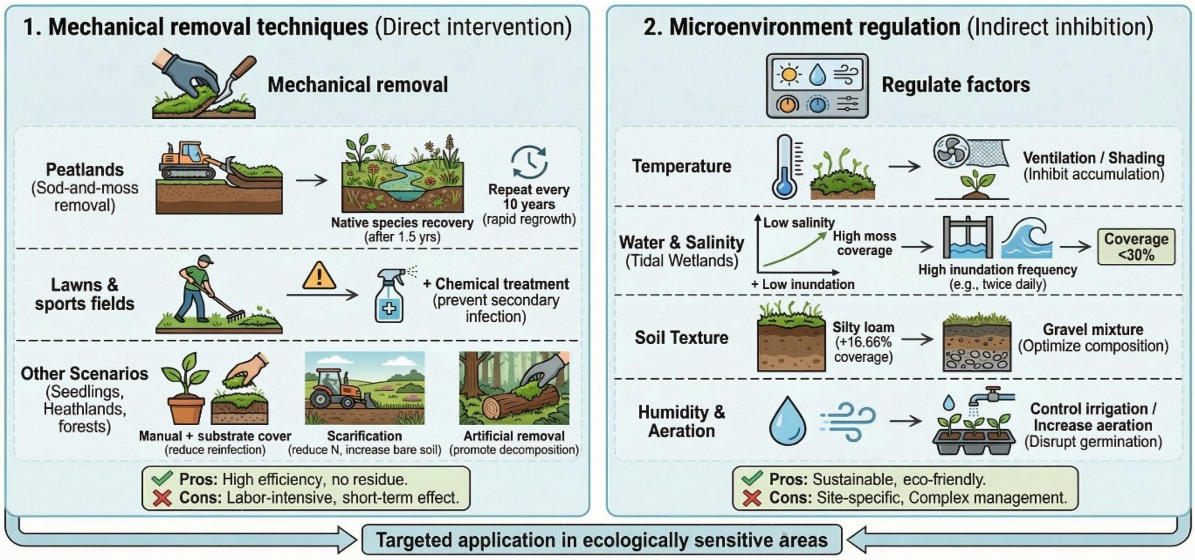

Figure 3. Physical control techniques for mosses, highlighting mechanical and microenvironmental approaches. Image generated by Gemini Pro and revised by the authors.
Abbreviation: N: Nitrogen.

mechanical removal is highly effective, it lasts for a relatively short time and thus requires regular management and incurs higher labor costs.

5.2. Microenvironment regulation

Moss growth is highly sensitive to microenvironmental factors—such as temperature, humidity, soil texture, salinity, and inundation frequency—and can thus be indirectly inhibited by modulating these factors.[11,21,22] In cross-regional forest surveys, annual mean temperature is identified as a key determinant of understory moss biomass, with low-temperature environments (high latitudes and high altitudes) facilitating significant biomass accumulation due to reduced decomposition rates. Therefore, regulating local microclimates to increase ambient temperatures, such as through silvicultural practices that improve forest ventilation and reduce excessive shading, can indirectly inhibit moss growth by accelerating organic matter decomposition.[21]

In tidal wetland ecosystems, the highest moss coverage occurs under the combination of low salinity and low inundation frequency (twice a week), while high inundation frequency (twice a day) reduces coverage to less than 30%; thus, moss regulation can be achieved by adjusting water levels through engineering measures. Soil texture also affects moss growth. Silty loam can increase moss coverage by 16.66% compared to gravel mixtures; thus, optimizing soil particle composition in seedling substrates or green space transformation can inhibit moss growth.[11] Meanwhile, controlling irrigation humidity and increasing substrate aeration can disrupt the environment for moss germination, thereby reducing competitive pressure from moss on seedlings.[22]

6. Ecological management strategies for mosses

Ecological management achieves a balance between moss suppression and ecological protection by regulating species competition, optimizing habitat functions, and formulating comprehensive plans in combination with site-specific conditions.[4,23,24] It is applicable to scenarios that require long-term maintenance and areas that require ecological restoration. Research in this area should take into account both short-term and long-term ecological effects. Figure 4 depicts the ecological management framework for mosses, which centers on regulating interspecific competition, optimizing habitat conditions, and striking a balance between moss suppression and ecological conservation.

6.1. Regulation of species competition relationships

The competition between vascular plants and mosses can indirectly inhibit the growth of mosses. In temperate European steppe ecosystems, the coverage and height of vascular plants are the core factors influencing moss diversity. Dense and tall vascular plants significantly reduce the species richness of moss by blocking light and competing for space. Research has shown that altitude gradient does not directly affect moss growth,

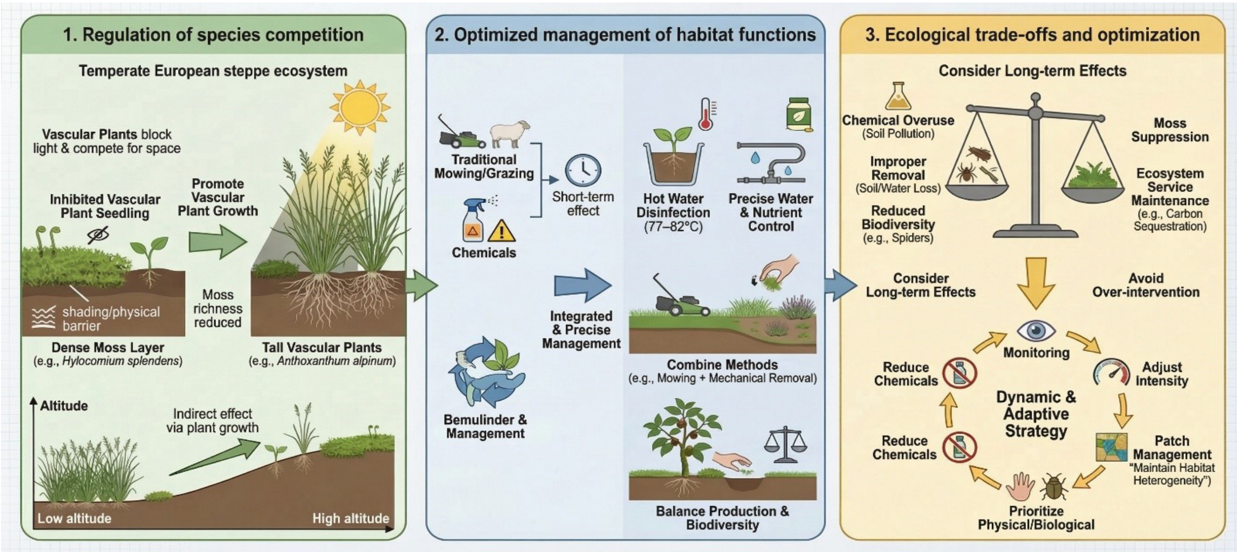

Figure 4. Ecological management strategies for mosses, illustrating the balance between suppression and ecological protection. Image generated by Gemini Pro and revised by the authors.

but indirectly influences it by altering the growth state of vascular plants—vascular plants grow poorly at high altitudes, resulting in less competitive pressure on mosses and thus increased diversity.[23]

In calcareous grasslands, dense moss layers significantly reduce the germination rate of vascular plant seeds and the survival rate of seedlings through physical barriers and shading effects.[4] Thus, the success rate of some vascular plant establishment can be increased after the moss layer is removed.[24] In mountain steppe ecosystems, moss is not a mere gap-filling species—its presence creates patches. After moss removal, species with high rates of renewal, such as *Anthoxanthum alpinum* and *Deschampsia flexuosa*, show a positive response in areas with high initial moss density.[25]

In heathland ecosystems, the accumulation of moss layers contributes to nitrogen enrichment by retaining atmospheric nitrogen deposition and facilitating nitrogen fixation via symbiotic cyanobacteria. Moderate grazing, as a traditional management practice, can regulate the structure of vascular plant communities (e.g., adjusting coverage, height, and species composition) and indirectly enhance competitive pressure on mosses through intensified competition for light and nutrients.[6]

The strong tolerance of *Hylocomium splendens* to extremely low temperatures poses a challenge to the suppression of this moss. It is widely distributed in the northern coniferous forests of the Northern Hemisphere, has photosynthetic structures that can tolerate low-temperature stress from −20 °C to −80 °C, and is significantly adapted to dehydrated environments, only showing instability under hydrated conditions at temperatures above 40 °C. Its unique environmental adaptation mechanism enables successful colonization and expansion in cold regions, suggesting that, when controlling moss in northern ecosystems, low-temperature interventions should be avoided, and its sensitivity to high temperatures can be exploited to enhance inhibition, for example, through measures such as temperature increase.[7]

Changes in vegetation structure caused by global warming are significantly affecting moss coverage and ecosystem invasibility in the subarctic heathland ecosystem. The regulation of moss and litter removal can significantly increase the germination rate of seedlings of alpine sweet vernal grass and *Betula nana*, but there are notable limitations in the subsequent survival stages—although moss removal generally promotes summer survival and first-year seedling establishment, it leads to a high mortality rate of *B. nana* seedlings in early August. This indicates that mosses play a dual role in subarctic habitats, contributing to both competitive inhibition and microenvironmental protection.[26]

6.2. Optimized management of habitat functions

In eutrophic peatland ecosystems, traditional mowing, grazing, and other management measures can keep moss coverage at a low level for a short period of time. However, a single year of mowing cannot stop the expansion of acidic peat moss, and mechanical removal techniques must be combined to achieve ecological restoration goals.[12] In container seedling management, a combined strategy of "pre-sowing disinfection + growth period monitoring" is adopted: disinfecting seedling containers by soaking in hot water (77–82 °C for 1 min) before sowing, and using drip irrigation for water control and precise fertilization to avoid nutrient excess during the growth period, which can significantly reduce the risk of moss colonization.[19]

In lawn management, after the application of sulfentrazone and other agents in spring, adjusting mowing height and optimizing nutrient input in autumn can enhance the competitiveness of lawn grass, thereby suppressing the growth of silver line moss over an extended period.[8] In heathland ecosystems, a combined management model of mowing and moss removal is adopted to control moss growth.[6] In coffee plantations, removing epiphytic moss can increase coffee fruit yield but significantly reduce epiphytic biodiversity; therefore, a balance between production demand and biodiversity conservation is needed.[27]

6.3. Ecological trade-offs and optimization of management strategies

Moss management should take into account long-term ecological effects and avoid the negative consequences of short-term suppression. Improper removal of moss in some areas may change the soil microenvironment and reduce water and nutrient retention capacity.[28] In northern peatlands, moss removal can suppress methane emissions, with the inhibitory effect becoming significant in the long term (e.g., after three years of removal) and being more pronounced in wet years,[29] but its potential impact on soil carbon sequestration functions requires further research and validation. In heathland ecosystems, high-intensity moss removal increases bare soil coverage but reduces the functional diversity of spiders. Therefore, the optimization strategy should include:

(i) Using patch management to preserve some moss habitats and maintain ecosystem service functions.
(ii) Dynamically adjusting the intensity of management in combination with monitoring data to avoid over-intervention.
(iii) Prioritizing physical and biological regulatory means and reducing the frequency and dosage of chemical agents.

Management intensity needs to be adjusted according to the scenario: (i) low-intensity management (e.g., mowing) can maintain habitat heterogeneity and is suitable for scenarios where biodiversity conservation is required; and (ii) high-intensity management (e.g., mechanical moss removal) is suitable for areas with severe moss damage, but the scope and frequency of implementation need to be controlled.[6]

7. Environmental adaptability and control difficulties of mosses

Mosses exhibit strong adaptability, diverse reproductive strategies, and significant interspecific variations, all of which pose considerable challenges to their control.[1] Therefore, a deep understanding of their environmental response mechanisms is key to improving control effectiveness. At the same time, it is necessary to address issues such as species specificity and reproductive diffusion to develop more precise and efficient moss removal methods. Table 1 provides a comparative overview of moss control and prevention techniques, summarizing their advantages, limitations, and applicability across different scenarios.

7.1. Environmental adaptability characteristics

Mosses are nearly ubiquitous across the globe, and their strong environmental adaptability is closely linked to the natural and climatic characteristics of different regions, which shape their diverse survival and distribution strategies. Investigations of elevational gradients show that the abundance of epiphytic moss species on the trunks of *Cryptomeria japonica* in the Darjeeling Hills of India exhibits a multimodal pattern, with precipitation, temperature stability, and solar radiation being the key climatic factors driving this distribution.[30] In the European dune ecosystem, the interactions between mosses and annual plants exhibit strong interannual shifts, with the intensity of these interactions showing a consistent variation trend along the latitudinal gradient: facilitation dominates in the first year and transitions to competition in the second year, and both facilitation and competition gradually weaken from south to north.[31]

Mosses in tidal wetlands have evolved specific adaptability to regional salinity and inundation frequency, with salt-tolerant species such as *Funaria hygrometrica* maintaining high coverage in low-salinity environments.[11] For polar and high-altitude cold regions, mosses develop unique cold resistance mechanisms to cope with extreme climatic conditions, while climate differences at different altitudes shape the functional trait networks of mosses—mosses at high altitudes enhance stress resistance by accumulating starch and soluble proteins.[32] These region-specific adaptations directly affect the effectiveness of suppression measures, which further highlights that moss control methods must take into account the natural and climatic characteristics of the target regions.

7.2. Core challenges in control

The multi-path reproduction strategy of moss increases control difficulty. The reproduction methods include spore dispersal, vegetative body fragmentation, and bud cup reproduction (e.g., the gemmae cups of liverworts), where bud cup fragments can spread via water splashes over a distance of up to 1 m.[19] In eutrophic peatlands, the recovery of the target mosses is limited by dispersal ability; many endangered moss species rarely produce sporophytes, while habitat fragmentation limits the dispersal of

Table 1. Comparative overview of moss control and prevention techniques by application scenarios

Types of suppression techniques	Main application scenarios	Key technologies/ agents/measures	Core effects	Advantages	Limitations/considerations
Chemical inhibition	Container seedling bases, golf courses, and epiphytic moss control areas	Quinoclamine, carfentrazone, and Asulox	Significant control efficacy and rapid results; inhibits the development of moss propagules	Efficient and rapid, suitable for large-scale hazardous scenarios	Multiple applications are required; some agents pose phytotoxicity; species sensitivity varies significantly, with high susceptibility to resistance development
Biological control	Golf course, grassland ecosystem, and scenarios requiring ecological protection	*Alternaria solani* and *Sclerotium rolfsii*; moss extract; development of targeted gene-killing proteins	The moss green coverage can be reduced to below 20% within 14 days; indirectly enhancing the competitiveness of target plants	Environmentally friendly, reducing the risk of pesticide use; strong host specificity and high ecological safety	Primarily at the laboratory stage; weak field colonization adaptability; immature large-scale cultivation technology; highly susceptible to environmental factors
Physical control	Ecological sensitive area, degraded peatland, lawn, container seedling bases, heather wasteland, and subtropical forest	Mechanical/manual removal; regulation of temperature, water level, and soil texture; control of irrigation humidity	Short-term effects are good; can drive ecosystem reversal; promotes litter decomposition; coverage can be reduced to less than 30%	Environmentally friendly, with no chemical residues; suitable for ecologically sensitive areas	Mechanical removal has a short maintenance period and requires frequent operations; microenvironment regulation demands high technical requirements; the effectiveness varies significantly across different scenarios
Ecological management strategies	Long-term maintenance of the landscape, ecological restoration area, eutrophic peatland, coffee plantation, and heathland	Regulate competition in vascular plants and implement moderate grazing; pre-planting disinfection + growth stage monitoring; patch management with dynamic adjustment	Long-term suppression of moss growth; improvement of target plant establishment success rate; balance between production and biodiversity	Balancing short-term effects with long-term ecological impacts; demonstrating strong sustainability; mitigating the adverse effects of chemical/physical interventions	Multiple technologies need to be synergistically integrated; management plans must be personalized to adapt to specific scenarios; long-term monitoring and adjustments are required

propagules.[12] There are also significant species differences in the tolerance of mosses, such as *C. stellatum*, which can maintain reproductive capacity under salt stress, while *T. nitens* shows a significant decline in reproductive capacity under submerged conditions.[11]

The significant interspecific differences in mosses have also led to uneven effectiveness of the same control methods for different species, making it difficult to develop universal control techniques. Different mosses show significant differences in tolerance to chemicals, such as *P. commune* being highly sensitive to Asulox, while *W. fluitans* is the most tolerant.[14] Some species also have unique adaptation mechanisms, such as *H. splendens*, which is highly adaptable to dehydrated environments. This interspecific specificity often limits the effectiveness of universal control strategies in practical applications.[7]

8. Practical recommendations for decision-makers

This section synthesizes the core characteristics of mosses—global distribution, strong environmental adaptability, diverse reproductive strategies, and dual ecological roles—and integrates findings from four control approaches to analyze key management trade-offs and propose practical recommendations for decision-makers.

8.1. Zoning management by ecosystem type

(i) Natural ecosystems (e.g., polar peatlands, subtropical forests, and tidal wetlands): Protect moss as a key ecosystem component, prohibiting large-scale removal and conducting only patch-wise suppression if invasive moss disrupts native communities[12] or threatens endangered plants,[4] using low-disturbance manual removal.
(ii) Human-dominated areas (e.g., seedling bases, golf courses, and walkways): Suppress excessive moss growth to mitigate crop yield loss[3] and maintain coverage at moderate levels (e.g., lawns[8]) to balance habitat functional demands and microecological stability.

8.2. Scenario-specific technical selection

(i) Container seedling cultivation: Prioritize quinoclamine (0.3–0.6 g/L, low phytotoxicity[3]), manual removal, and substrate covering.[19]
(ii) Golf courses/lawns: Apply carfentrazone, sulfentrazone, and *A. solani*,[10] combine with mowing and nutrient optimization,[8] and rely on copper-based formulations for low-risk continuous management.[5]
(iii) Urban walkways: Use lime-derived formulations to promote rapid moss shedding[15] while leaving minimal residues.
(iv) Agricultural plantations: Combine manual removal of epiphytic moss with moderate pruning.[15]

8.3. Climate-adapted adjustments

(i) Polar/high-altitude cold zones: Apply summer microclimate regulation to target heat-sensitive moss.[7]
(ii) Subtropical/tropical humid zones: Adjust physical removal frequency—reduce during rainy periods and increase during dry periods.[20]
(iii) Tidal wetlands: Control moss coverage by regulating inundation frequency (twice daily[11]).
(iv) Temperate zones: Enhance vascular plant competition against moss through moderate grazing and mowing.[6]

9. Research prospects and future directions

Current moss control and prevention techniques still face multiple challenges, including:

(a) Chemical agents lack species specificity, posing environmental risks and promoting resistance.
(b) Biological control agents exhibit limited field stability and underdeveloped large-scale cultivation techniques.
(c) Physical regulation provides insufficient long-term effectiveness.
(d) Ecological management has a narrow application scope and shows significant spatiotemporal variability in outcomes.

The limitations of individual techniques highlight the need for integrated, scenario-based management strategies as the future direction. Accordingly, future research should focus on:

(a) Research and application of chemical and biological agents
  (i) Develop low-toxic, high-efficiency, and cost-effective chemical agents to improve efficacy and minimize environmental impact.
  (ii) Incorporate nano-formulation technologies to enhance targeting and mitigate effects on non-target organisms.
  (iii) Investigate the pathogenic mechanisms of biocontrol microorganisms, develop stable biologic formulations, and enhance field performance.
  (iv) Optimize application timing and dosage to minimize interventions, reduce environmental impact, and lower management costs.

(b) Technology integration and scenario adaptation
  (i) Integrate multiple control and management

techniques to develop scenario-specific, region- and climate-adapted strategies, taking into account the natural and climatic characteristics of target areas (e.g., polar cold, subtropical humidity, boreal dryness).

(ii) Utilize technical tools, including remote sensing observations and geographic information systems, for planning control strategies, monitoring efficacy in real-time, and optimizing scenario-specific management.

(c) Interdisciplinary research and target discovery

(i) Investigate the chemical and biological mechanisms by which ethylene regulates the three-dimensional growth of mosses and identify additional suppression methods,[33] including in-depth analysis of interactions between mosses and other organisms (e.g., vascular plants, microorganisms).

(ii) Apply isotope labeling techniques to elucidate the migration and transformation of agents in the moss–soil–microbial system, providing theoretical support for the development of novel inhibitory agents and ecological management approaches.

(d) Long-term ecological effects assessment

Implement long-term monitoring and research to evaluate the impacts of different control measures on ecosystem structure and function—including biodiversity and nutrient cycling—to ensure moss management is compatible with ecological protection objectives.

10. Conclusion

This review summarizes the technical traits, strengths, and limitations of four moss control strategies: chemical inhibition, biological control, physical regulation, and ecological management. We outline core management principles: zoning by ecosystem type, scenario-specific technical choice, and climate-adapted adjustment. Given the limits of single techniques, integrated scenario-based management represents the optimal path for future moss control. Future work should prioritize efficient, low-risk agents and stable biological products, combined with long-term ecological assessments, to support sustainable moss management compatible with ecological protection.

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Conflict of interest

The authors declare no conflicts of interest.

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Not applicable.

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