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BRYOPHYTES AS REGULATORY ECOSYSTEM SERVICES PROVIDERS IN THE URBAN LANDSCAPE

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Abstract. Human survival, health and well-being depend directly on ecosystem services or the benefits humans derive from ecosystems. Regulatory ecosystem services are essential to humans, as they represent services that regulate the environment, such as climate regulation, clean air and water availability, and flood control. Different plants provide ecosystem services in cities, but the authors focus on bryophytes (or mosses) in this article. Moss's ability to provide ecosystem services is represented broadly in the literature, but there is no systematized approach to view them. Therefore, the author's objective of the study is to develop systematization and answer the research question "What ecosystem services provided by mosses to the urban landscape should be included in the systematization of regulating ecosystem services?". To answer the question, authors fulfilled such tasks as analyzing theoretical sources on the ecosystem services provided by mosses in urban landscapes; to develop a systematization of the regulating ecosystem services and benefits mosses provide to the urban landscape, using systemic analysis. After the execution of the analysis, regulatory ecosystem services provided by mosses were prepared in a systematization depicting interactions and implications. Identified ecosystem services provided by mosses that fulfil regulatory services include improving air quality, photosynthesis of CO2 into oxygen, rainwater retention, reduction of the heat island effect, promotion of biodiversity, reduction of noise pollution, and mitigation of the long-term impact of climate change. The research rationale is novel in its outcome, as there is a current gap in knowledge of a structured, systematized summary of regulatory ecosystem services provided by mosses. These finding carry both theoretical and practical value, as they can be used both for study purposes and envidening view on ecosystem services and specific plants providing them; at the same time from practical perspective, this research brings a framework for policy makers, urban planners, and landscape architects on regulatory ecosystem services provided by mosses.
Keywords: regulatory ecosystem services, moss ecosystem services, moss systematization, mosses in landscape architecture, landscape architecture students

Introduction

Most people live in cities and urban environments today- nevertheless, human survival depends directly on nature and ecosystems [3]. Cities depend on ecosystems beyond city borders and benefit from internal urban ecosystems [10]. Ecosystem services refer to the benefits humans derive from ecosystems, which contribute to public health and improve the well-being of urban residents [3]. The EU Nature Restoration Regulation (entered into force on 18 August 2024) promotes the ambitious restoration of natural and environmental values and the improvement of urban green spaces, while adapting to climate change. The Regulation follows the framework of the green economy, the green deal and ecosystem services [34]. Ecosystem services, systematisation and assessment are the starting point for nature's contribution to humans. The concept of ecosystem services was introduced in the 1980s to highlight human dependence on the natural environment [8, 17, 26]. To categorize ecosystem services, authors chose to use the Millennium Ecosystem Assessment [6] as it provides a globally accepted typology of ecosystem services, making it suitable for international view and comparison of ecosystem services. According to it, the classification system can be divided into four main categories:

1. Supporting: services that are essential for soil formation and the circulation of nutrients in nature;
2. Provisioning: directly usable services, such as food, materials, and energy;
3. Regulating: services that regulate the environment, such as climate, access to clean air and water, flood control, etc.
4. Cultural: services that provide recreation, spirituality, and aesthetic aspects [29].

This article focuses on regulating ecosystem services and the role of bryophytes (or more commonly used – mosses) in providing them, as mosses have a unique ability to grow on a variety of substrates [25] that are unsuitable for any other plant and, despite their small size, mosses account for a significant proportion of the world's plant biomass [33]. Unlike all other plants, mosses are found everywhere, on all continents, from deserts to the Arctic, except in seas and oceans [18]. Species that grow in, for example, Europe may also be found elsewhere in the world, such as Asia or America [19]. Many mosses grow in urban environments, providing a range of ecosystem services [9] due to their natural growth in cities and the influence of human activities (for example, using mosses for green infrastructure). Bryophytes are the second-largest group of plants in the world, surpassed only by the angiosperms – flowering plants [24]. Botanically, mosses are nonvascular plants in the land plant division Bryophyta. Mosses are among the first plants on Earth, having survived for over 400 million years [32], enduring all climate changes and developing robust survival mechanisms [19]. There are approximately 12,000 species of mosses, which occupy more than six million square kilometres of land and are ecologically and evolutionarily important [24]. Central Europe, especially the mountainous regions of the Alps and, to some extent, Scandinavia, Scotland, Wales, the Pyrenees, and Eastern Europe, has the highest number of moss species. Species richness gradually decreases towards the south and east of Europe [20]. Mosses provide a range of ecosystem services that are important for both humans and life on Earth in general:

1. Some moss species have adapted to survive in extreme conditions. Studies have shown that the temperature at which mosses freeze is -3 to -8 ºC, depending on the species; the lowest air temperature at which they can photosynthesizes is about -5 ºC, and the highest is about 30 ºC [37]. To survive extreme heat, mosses dry out, as this allows them to tolerate high temperatures better. Studies indicate 120 ºC is the highest temperature that some moss species can tolerate for a short time [38]. After periods of drought, when mosses are fully hydrated, they quickly resume their metabolism upon rewetting [19]. Mosses also affect soil temperature,

protecting the soil from immediate heating in hot weather and acting as a layer between air temperature and soil in cold weather, thereby achieving higher soil temperatures [38]. The regulation of soil temperature and moisture is an essential component of the overall ecosystem's health, as it controls the concentration of nitrogen available to plants [36]. For example, the moss species Homalothecium sericeum, Barbula unguiculata, Pseudoleskea incurvata, Grimmia pulvinata, and Hypnum cupressiforme have been proven to reduce surface temperatures by up to 14 °C in a specific application.

2. Mosses have played a crucial role in ecosystem processes over centuries—permafrost formation and thawing, peat accumulation, and microtopography development. Mosses account for the majority of biodiversity [24]. For example, bogs form ecosystems fundamentally dependent on mosses [20]. Moses also provides habitat for various organisms [36], shelter and food for small invertebrates, and nesting material for birds and mammals.

3. The ability of bryophytes to regenerate and grow from any fragment, a feature called fragmentation, vegetative reproduction, or asexual reproduction, makes them remarkably resilient and is partly a result of totipotency - the ability of any cell in the organism to dedifferentiate and then differentiate into a new plant. All bryophytes are totipotent to some extent: they can regenerate from a fragment or even a single cell, making them excellent survivors [19]. The authors have researched this unique feature of mosses and identified moss species Brachythecium albicans, Brachythecium rutabulum, and Bryum argenteum as the most resilient, mainly when cultivated in combination [15].

4. Reducing plant pathogens and increasing carbon sequestration in the soil, thereby improving overall soil health, is an essential function of mosses. Mosses also protect long-term carbon storage systems such as bogs and permafrost. Moss growth is increasingly being incorporated into models to enhance the accuracy of climate change projections [24]. Mosses act like sponges, using capillaries to hold onto water. They help absorb precipitation, retain moisture in the soil below, and maintain moist conditions around them. This allows other plants to thrive around them, such as in habitats such as swamps and forests [22]. Given the moss's uptake capacity, a moss mat can act as a reservoir that traps large amounts of nutrients in an ecosystem [5]. Studies indicate that mosses can store 8–10 times their weight in water [1,12].

5. Mosses play a critical role in the global carbon cycle as the largest carbon store on the planet [19]. Because mosses are small, they grow close to the soil surface and are exposed to Carbon Dioxide (CO2) released by decomposing soil organic matter. Thus, mosses are likely exposed to significantly higher levels of CO2 than most other plants. Unlike vascular plants, mosses do not use stomata to take up CO2 and may have less access to available CO2. A team of researchers from the Pandey and Allen laboratories at the Donald Danforth Center for Plant Science at Danforth University addressed this issue. It demonstrated that the spongy bladderwort Physcomitrium patens, a moss species, produces three times more biomass under elevated CO2 conditions by adapting its growth, metabolism, and physiology, primarily through changes in sugar-nitrogen interactions. These results suggest that the increase in biomass is due to improved photosynthesis and a balance in the moss life cycle between diffuse and abundant growth, depending on nitrogen and carbon availability [24]. It has been estimated that soil covered with moss globally contains 6.43 Gt more CO2 than bare soil [9].

6. Mosses are also unique plants due to their capacity to achieve high levels of air purification, especially under conditions of stable temperature and humidity [2], as they can withstand high levels of salinity, accumulate metals and such air pollutants as Particulate Matter (PM) [27]. This property is facilitated by mosses having rhizoids instead of roots. This means mosses have evolved to obtain nutrients from the air or surrounding water by taking up particles with their leaves [14]. The authors measured PM absorption efficiency in a laboratory setting, and an efficiency of over 40% was found for moss species such as Dicranum scoparium, Hypnum cupressiforme, and Plagiomnium affine [16].

7. Mosses may mitigate noise pollution. Although the market for sound-absorbing moss walls is quite active in Europe and globally, there is a gap in scientific knowledge regarding the efficiency of moss in absorbing noise pollution. Some studies [27;31] indicate that mosses can be a sound barrier. However, further research must determine the sound-absorbing characteristics of different moss species and placements.

Although there is sufficient literature on mosses and their provision of ecosystem services, the authors have identified a gap in current knowledge of unified systematization that covers summarized information on this topic. Therefore, this Article provides summarized information in a unified form.

Methods

This Article aims to systematize the regulating ecosystem services provided by mosses and their benefits in the urban environment and to answer the research question, "What ecosystem services provided by mosses to the urban landscape should be included in the systematization of regulating ecosystem services?" by covering the following tasks:

1. Analyze theoretical sources on the ecosystem services provided by mosses in urban landscapes.
2. Using systemic analysis, develop a systematization of the regulating ecosystem services and benefits mosses provide to the urban landscape.

To summarize the information obtained and to establish a correlation between the ecosystem services provided by mosses and the benefits in the urban landscape, the authors developed a systematization. Systematization is organizing qualitative data through categorization and thematic analysis to gain consistent insights into a specific topic [11]. Systematization is essential for aligning research questions, methods, and analysis in a structured manner to ensure the validity and reliability of conclusions [7].

Systematization components include:

1. Identifying the purpose - when starting systematization, it is essential to identify the purpose of the research, which also includes posing research questions or hypotheses [7];
2. Conceptual development - the conceptual framework is the basis for understanding and understanding the research question through various research methods and their analysis, systematically organizing and interpreting data [23];
3. Data acquisition and categorization - a structured approach to data acquisition and processing should be divided into categories for further analysis [11], a predefined scheme for analysis ensures consistency [21];
4. Analysis - the most essential part of research, using various analysis methods that ensure systematic interpretation of data [4];
5. Validation (or approbation) - criteria such as reliability, transferability, and confirmability indicate the approbation [13] or confirmation of the study;
6. Synthesis - drawing conclusions, accompanied by clear visual and textual presentations [7].

The article's authors conclude that systematization is fundamental to a successful research outcome. After analyzing the theoretical framework, they elaborate on the results.

TABLE 1

Systematization of moss-regulating ecosystem services and benefits [created by author's]

An indicator of regulating ecosystem services provided by mosses in urban environments	Ecosystem service explanation	The impact of moss	Benefit for humans
Improving air quality by reducing pollution	Primary services include plant growth, human respiration, and biogeochemical cycling. Secondary services (depending on the primary) are, for example, clean drinking water and its availability, wood for producing further products, environment for recreation and tourism, etc.	Mosses, plants, and GI barriers in urban environments are essential to the overall ecosystem, as they capture pollutants. The moss species Dicranum scoparium, Plagiomnium affine, and Hypnum cupressiform have an average efficiency of more than 40% in reducing PM pollution under laboratory conditions.	Fresh air is one of the basic elements of the vital functions of all living things, including humans. Air pollution causes 8 million premature deaths worldwide. It affects diseases such as cardiovascular and respiratory diseases.
CO2 is photosynthesised into oxygen	Photosynthesis is the process by which plants take CO2 and H2O from the air and soil, converting these compounds into glucose and oxygen. Some of the oxygen is released back into the atmosphere. All plants perform photosynthesis, which is necessary for exchanging gases in the atmosphere, including those involved in human respiration.	Mosses absorb CO2 and H2O on their entire surface throughout the year, depending on air temperature to varying extents. Some studies confirm that some moss species have increased CO2 uptake and oxygen release.	Air containing sufficient oxygen is necessary for humans and animals to maintain their vital functions.
Rainwater retention	When rain falls in an urban environment, it is crucial to drain or absorb excess water to prevent flooding, which can harm the city's infrastructure and human life.	Depending on the species, mosses absorb water. Some species absorb up to 10 times their dry weight in water.	Improper rainwater collection can lead to flooding, which in turn can result in various injuries, infectious diseases, and even death.
Heat island mitigation	Heat islands are areas within a city that have significantly higher air temperatures than their surrounding areas. Mitigating heat islands is an essential ecosystem service that GI addresses in cities.	Moss species such as curly moss Homalothecium sericeum, blunt-leaf barbel Barbula unguiculata, scaly-footed Pseudoleskea incurvata, pad grimmium Grimmia pulvinata and cypress hypnum Hypnum cupressiforme reduce air temperature in urban environments by up to 14 °C.	The heat island has adverse effects on human health and a secondary impact on humans, as its primary effects include air pollution, degradation of groundwater quality, and loss of biodiversity.
Promoting biodiversity	Biodiversity refers to the variety of organisms on Earth, and the loss of biodiversity has significant implications for life processes on Our Planet. Biodiversity is a prerequisite for life on Earth.	Mosses in urban environments influence the attraction of other organisms to this environment, provide valuable shelter for insects, shelter and food for small invertebrates, and nesting materials for birds and small mammals. Additional research on mosses as a habitat for microbes is needed.	The diversity of nature has a profound impact on humans, and without it, life on Earth would be unimaginable.
Reducing noise pollution	There are many different types of noise in urban environments, and reducing sound pollution is an essential GI ecosystem service in urban environments.	GI, including moss, when installed appropriately (e.g. in the placement of green walls), can significantly reduce noise.	Noise pollution causes adverse effects on the cardiovascular system and metabolism, reduces children's cognitive performance, and causes severe irritation and sleep disturbances.
Long-term impacts of climate change	Urban ecosystem services have a significant impact on climate change in the long term.	Mosses, the first plants on Earth, have developed strong survival mechanisms that have enabled them to endure all climate changes. As an essential part of the ecosystem, they also impact the climate and contribute to climate change.	Well-being, comfort, health and survival to a greater or lesser extent (depending on location).

Results

The article's authors identify the ecosystem services that mosses provide (Table 1), their impact, and the benefits they offer to humans.

The authors examined ecosystem services in relation to their impact on humans, creating a schematic drawing (Figure 1) that illustrates the consequences for humans and nature if ecosystem services are not provided, as well as the benefits to humans if they are provided. The authors conclude that mosses, as a provider of ecosystem services, have the most significant impact on human well-being and comfortable living. They also significantly impact human health, primarily physical, but ecosystem services also affect mental health. And if ecosystem services are not provided, the negative impact is most substantial on human health, mainly affecting cardiovascular diseases, death, or the disappearance of life on Earth.

After analyzing the theoretical literature and conducting empirical research on systematization preparation, the authors have achieved the article's goal. They have developed a systematization that will serve as a basis for further research on this topic and can serve as a guide or component of methodological material in urban planning in the public sector, for example, in municipalities.

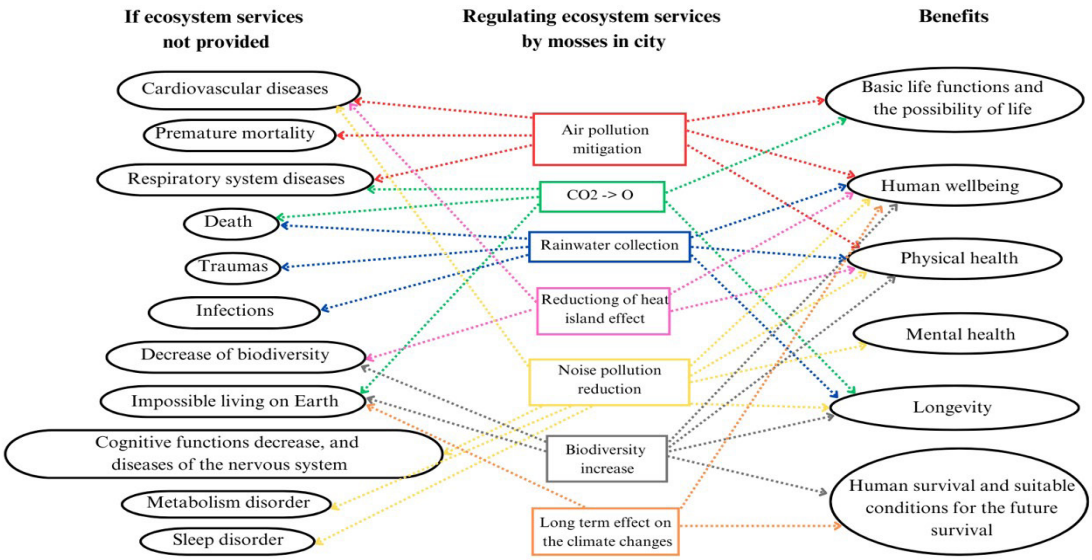

Fig. 1. Scheme of regulating ecosystem services and benefits provided by mosses [created by author's]

Discussion

This systematization shows a novel approach to viewing mosses in urban environments and valuing their presence that occurs naturally in cities. People also bring a form of green infrastructure to towns, for example. It is essential to provide an overall summary of the regulatory ecosystem services provided by mosses, as this highlights the enumeration of ecosystem services and their interactions and impacts, both positive and negative. Suppose these ecosystem services are not offered in cities by mosses. In that case, there are various implications, ranging from a mild effect on human well-being to natural hazards and even long-term consequences for human survival. On the contrary, if mosses are integrated into the city landscape by landscape architects, urban planners, and policymakers, a long-term positive impact will be evident for humans. For systematization it is essential to align the research question, methods used, and data from analysis. The outcome is presented in a structured manner that ensures validity and reliability.

There is a scaling possibility and practical application of this systematization as well - it can be used globally, as analyzed literature covers global research, and all the chosen moss species are cosmopolitan - they can grow worldwide. At the same time, the practicality of this research result lies in its possibility of instant use by urban planners and landscape architecture students as a broader view on the ecosystem services topic and determination of plants for an urban environment. Although this study did not research other plants, except mosses, an application can be valuable, but it must be considered in the context of the overall objectives of landscape architecture.

Conclusions

After analyzing the theoretical literature and conducting empirical research, the authors of the article have achieved the objectives of the work: a systematization of the regulatory ecosystem services and benefits provided by mosses in the urban environment has been developed. The authors of the article created a systematization that could serve as a basis for further research on this topic, as well as serve as guidelines or a component of methodological material in urban planning in the public sector, for example, in municipalities. This systematization can also be implemented in educational programs about ecosystem services and various plants that provide them. According to the systematization developed by the authors, the regulatory ecosystem services provided by mosses in the urban environment are air quality improvement, CO2 photosynthesis into oxygen, rainwater retention, heat island effect reduction, biodiversity promotion, noise pollution reduction, and long-term impact of climate change.

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Kopsavilkums

Strauji pieaugot urbanizācijai, pilsētām ir aizvien nepieciešami efektīvi ekosistēmu pakalpojumi, un briofīti jeb sūnas ir spēcīgs, bet bieži vien nepietiekami novērtēts resurss šo vajadzību apmierināšanai. Pētījuma galvenā problēma ir vienota, sistemātiska ietvara trūkums, kas apkopotu sūnu sniegtos regulējošos pakalpojumus pilsētvidē. Tāpēc šī darba mērķis bija izstrādāt sistematizāciju, kas kalpotu kā praktisks rīks pilsētplānotājiem un ainavu arhitektiem. Pētījumā tika identificēti un sistematizēti septiņi galvenie regulējošie ekosistēmu pakalpojumi, ko sniedz sūnas. Šo pakalpojumu efektivitāti apstiprina konkrēti dati: sūnas spēj absorbēt ūdeni līdz pat desmit reizēm vairāk par savu sauso svaru. Tās var samazināt virsmas temperatūru pat par 14°C. Turklāt laboratorijas apstākļos ir pierādīts, ka atsevišķas sugas spēj no gaisa absorbēt vairāk nekā 40 % cieto daļiņu piesārņojuma. Šis sistematizētais ietvars sniedz ainavu arhitektiem uz pierādījumiem balstītu pamatojumu sūnu integrēšanai zaļās infrastruktūras projektos. Tas ir tieši piemērojams vertikālo dārzu, zaļo jumtu un inovatīvu zemes segumu risinājumu izstrādē. Nobeigumā, šis pētījums kalpo kā fundamentāls ceļvedis, kas ļauj dizaineriem izmantot sūnu unikālo bioloģisko noturību. Tas paver iespēju pārveidot pilsētas virsmas par augstas veiktspējas, pašpietiekamām ekosistēmām, kas uzlabo gan cilvēku labklājību, gan ekoloģisko veselību.

Pētījums arī iezīmē skaidrus virzienus turpmākajai izpētei. Tajā ir skaidri norādīts uz zināšanu trūkumu par sūnu skaņu absorbējošajām īpašībām un nepieciešamību pēc papildu pētījumiem par sūnām kā mikrobu dzīvotnēm. Šie identificētie trūkumi nosaka skaidru kursu nākotnes starpdisciplinārai pētniecībai.

Ainavu arhitekti, akustiskie inženieri un mikrobiologi varētu sadarboties projektos, lai:

1. Kvantificētu dažādu sūnu sugu un montāžas veidu trokšņa samazināšanas koeficientu (NRC), radot uz datiem balstītu katalogu akustiskajam dizainam.
2. Izpētītu unikālās mikrobu kopienas, kas mīt pilsētas sūnās, un to lomu bioģeoķīmiskajos ciklos vai patogēnu nomākšanā.