Expanding ecomimicry by studying the role of Bryophyta in ecosystems.

Improving urban water systems by studying hydrological moss ecosystem services

Open PhD proposal Science for Sustainability (UU) & Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)

Author: Nehizena Osagie (2749750)
Institute: Utrecht University (UU**)**
Programme: Bio-Inspired Innovation

Daily supervisor: Katharina Hecht, MSc (UU, Biology**)**
Examiner: Dr. Jaco Appelman (UU, Biology)
Second reviewer: Dr. Kathryn Barry(UU, Ecology & Biodiversity)

Keywords
Biomimicry, ecosystem services, ecology, Bryophyta, urban design

Abstract

The urban landscape is experiencing rapid expansion driven by population growth and urbanization, yet it faces mounting challenges from climate change and sustainability crises, including pluvial flooding in Dutch cities due to extreme precipitation events. Conventional urban infrastructure struggles to address these challenges, highlighting the need for holistic and systematic approaches to urban development. Natural ecosystems provide valuable insights for tackling contemporary environmental problems, with Bryophyta (mosses) emerging as key contributors to essential ecosystem functions and services. This doctoral research proposal aims to fill critical gaps in our understanding of Bryophyta (mosses) and their significance in generating hydrological ecosystem services within urban environments. Leveraging biomimicry principles, the study will adopt a multifaceted approach integrating rigorous scientific inquiry and applied ecological principles to comprehensively evaluate mosses' contributions within urban environments. By synthesizing biomimicry and systems thinking, the research aims to develop an ecomimicry framework that provides practical recommendations to support urban planners, policymakers, and designers in creating sustainable urban environments.

Summary

In the coming decades, it seems to be inevitable that more people will move to cities and thus cities will need to expand. As cities expand rapidly, they face increasing challenges from climate change. One such challenge in Dutch cities is flooding after heavy rainfall. Which shows the limitations of existing urban infrastructure. Increasing or changing this infrastructure is very costly and would need a lot of work. It becomes clear that traditional solutions aren't enough to solve the issue, so we need new ideas. By looking at the problem from a more zoomed-out perspective we can better address the key points. This perspective helps to analyse the problem by placing it in the context of a system. Also referred to as a systemic view. A good model for looking at larger systems that work well are ecosystems. Because they can show us how different organisms and elements work together.

Mosses are small plants that are often overlooked. Yet they appear to be crucial components of all types of ecosystems and generate positive benefits for other species. They hold on to soil making the ground less prone to erosion and easier for other plants to colonize. They help to increase local diversity by providing safe spaces and food for other organisms. Moss also plays an important role in water capture and storage, especially in young ecosystems. We call the positive effects that a species has on the well-being, ecosystem services. Because mosses provide so many positive services, this means that there are a lot of lessons we can learn from mosses to design our urban environments better. Unfortunately, we currently don’t have large numbers of mosses in cities. On top of this, we don’t fully understand how they generate positive benefits in ecosystems. This research project aims to fill important knowledge gaps about the role of mosses in urban environments and their contribution to essential ecosystem services, particularly related to water management.

By combining field observations with controlled experiments over the course of 4 years, the study seeks to understand how mosses influence the water cycle in cities. While also exploring how this knowledge can help to design more sustainable urban spaces. The PhD project will adopt a case study approach for the city of Utrecht. Field observations will be done at a few locations in the city of Utrecht and the Utrecht Science Park. The sites that will be used are monitored in multiple rounds for a period of 2 years. To compare results and control the environment, laboratory experiments will be performed. For these experiments, the most common moss species, and the types of surfaces they are found on the most will be used. Next to this, relevant professionals who work in the field of urban development will be approached for interviews and feedback.

By learning from nature, the project seeks to develop an easy-to-use tool. Which can aid urban planners and policymakers in creating sustainable cities, by providing practical steps they can take.

Table of Contents

Research topic

Introduction

The urban landscape appears destined for significant expansion in the coming decades, with both its area and population numbers on the rise (Eales et al., 2021). This expansion coincides with mounting pressure from climate change and sustainability crises (Perini et al., 2020). For instance, Dutch cities are experiencing a rise in pluvial flooding incidents due to an increase in extreme precipitation events (Dai, Wörner & van Rijswick, 2017). However, the existing infrastructure in Dutch cities, such as canals and sewage systems, cannot effectively manage the heightened precipitation. Particularly in densely populated urban areas, there are limitations in rainwater drainage, and the expansion of these infrastructure systems comes with significant costs and labour demands (Francesch-Huidobro et al., 2017).

Cities are best understood as complex systems, and addressing these pressing issues requires more than localized fixes (Eales et al., 2021). Instead, a holistic and systematic approach is necessary, which demands a broader perspective (Cristiano et al., 2020; Wolfram, Frantzeskaki & Maschmeyer, 2016). Within this intricate urban matrix lies the challenge of comprehending the broader system. Fortunately, natural ecosystems, despite being only partially understood, can serve as valuable mentors and models for tackling today's environmental problems (Hayes, Desha & Baumeister, 2020). Exploring the mechanisms behind ecosystem functioning and ecosystem service generation offers a crucial pathway for fostering sustainable urban development (Cooper, 2019).

Amidst the complexities, Bryophyta (moss), the often-underestimated botanical group, have been identified as key actors in ecosystems. Despite their small stature, mosses contribute substantially to vital functions and services within ecosystems at different scales (Bahuguna et al., 2013; Eldridge, et al., 2023). Their contributions to biodiversity support, nutrient cycling, soil stabilization, and water retention are increasingly acknowledged in natural systems, yet remain largely undervalued in urban contexts (Nagase, Katagiri, T & Lundholm, 2023; Perini et al., 2020; Thielen et al., 2021).

Recent studies have increasingly linked Bryophyta not only to ecosystem pioneering but also to the provision of multiple ecosystem services worldwide (Eldridge, et al., 2023). Bryophyta play a crucial role in delivering essential ecosystem services such as moisture retention and soil stabilization across a wide range of global habitats, from Antarctic heaths to arid deserts (Thielen et al., 2021). Moss has been identified as a key player in moisture capture and retention in early ecosystems (Jackson, 1971), contributing significantly to supporting various ecosystem services in locations where vascular plants have limited influence. Additionally, soil mosses have been found to contribute to multiple ecosystem services, with their effects on soils likely influenced by biological traits, climatic conditions, and soil abiotic stressors (Eldridge, et al., 2023). However, despite these advancements, our understanding of Bryophyta and their intricate relationship with ecosystem services remains scarce (Hu et al., 2023).

Bryophyta exhibit a remarkable ability to grow on a diverse array of substrates and environments, including man-made surfaces. Moss species have been observed thriving on various substrates such as tree bark, plastered and un-plastered walls, blocks, rock surfaces, sand, soil, and forest floors (Adebiyi and Oyeyemi, 2013; Bahuguna et al., 2013). However, human activities have historically hindered moss growth in urban environments (Fojcik et al., 2015; Richter, Schuütze & Bruelheide, 2009). In the previous century, this limitation stemmed from the initial removal of native plants due to urbanization (Duncan et al., 2011; Haynes et al., 2019), as well as indirect destruction caused by environmental changes and pollutants (Żołnierz, Fudali & Szymanowski, 2022). Although mosses have shown signs of resurgence in urban areas with improving air quality, they now face active removal by humans upon colonization of urban surfaces (Jang & Viles, 2022). These gaps in knowledge and negative attitudes towards Bryophyta impede their integration into urban environments, depriving cityscapes of potential benefits crucial for sustainable development.

Biomimicry holds the potential to translate enhanced ecosystem understanding into tangible learning points, such as effectively integrating Bryophyta and their ecosystem services generation in urban areas. Situated at the transdisciplinary border of biology and design, biomimicry is a new field with promising implications for sustainable solutions. Among the three primary bio-inspired design approaches—bionics, biomimetics, and biomimicry—biomimicry is distinguished by its strong focus on sustainability (Jatsch et al., 2023; Landrum & Mead, 2022). Jatsch et al. (2023) argue that elevating the field involves integrating academic research, laboratory findings, and practical applications to foster a more systemic approach. As scientific communities increasingly pivot towards addressing real-world challenges, frameworks that facilitate communication and collaboration, such as biomimicry, will continue to play a pivotal role in achieving these objectives (Partelow, 2023). Hayes et al. (2020), even argue that failing to consider system-level biomimicry can lead to solutions that do not necessarily enhance overall sustainability outcomes.

However, there is limited investigation of biomimicry at the systems level to date. In their literature study Hayes et al. (2020), found that only 4 of the 75 reviewed documents focused on 'system' or partial system-level biomimicry. Most of the publications detailed mimicry of a single organism or even just part of a particular organism to extract a relatively narrow design strategy. What is important for system-level biomimicry, however, is a recognition that ecological systems cannot simply be copied and implemented into urban systems. While both can be seen as complex systems, urban systems have a distinct set of unique characteristics related to human influence, such as the built infrastructure (Blanco et al., 2021). Thus systems-level biomimicry must be implemented within complex socio-eco-technological systems different from their natural context (Hayes, Desha & Gibbs, 2019). The current lack of integrated knowledge on ecosystem functioning and services generation hinders the effective application of ecosystem-level biomimicry in urban design (Blanco et al., 2021).

Addressing biomimicry at the systems level can be done by exploring Bryophyta's roles and contributions within the larger framework of ecosystems. Biomimicry could help to bridge the understanding of mosses at a systemic level and harness their inherent capabilities as a blueprint for sustainable urban design. Thus, bryophyte research in the context of ecosystem services could provide two positive outcomes. Firstly, by improving the understanding of the Bryophyta their numbers in urban environments could be greatly increased to gain direct benefits. Secondly, the improved understanding can lead to the abstraction of their role and functions, serving as a tool for sustainable urban design.

Overall aim & Research gaps

Leveraging biomimicry principles, this doctoral research aims to delve into the intricate interactions between Bryophyta and urban ecosystems, shedding light on their potential and suitability as nature-inspired solutions for sustainable urban development, specifically in terms of water capture.

The study will adopt a multifaceted approach, integrating rigorous scientific inquiry and applied ecological principles to comprehensively evaluate the roles and contributions of moss within urban ecosystems. By synthesizing biomimicry and systems thinking, the research will extract lessons from enhanced ecological understanding, aiming to bridge existing knowledge gaps and unearth the untapped potential of Bryophyta in generating ecosystem services in urban settings. Additionally, this research will initiate the development of an ecomimicry framework, laying the groundwork for more sustainable and climate-resilient systems.

The overarching goal is to devise a framework that provides valuable insights and practical recommendations to assist urban planners, policymakers, and designers in crafting resilient and sustainable urban environments by using and learning from Bryophyta. This framework should facilitate the identification of suitable ecological processes to address systemic issues such as flooding due to poor runoff management in the city. By shifting the focus towards understanding larger systems and drawing inspiration from natural ecosystems, both the academic and non-academic sectors stand to benefit greatly.

For instance, more moss cover in the city could enhance water capture. Mosses have demonstrated remarkable water storage capacities, ranging from 100 to 2070% of their dry weight, offering potential solutions for drought mitigation (Thielen et al., 2021). If urban rainwater management systems could mimic this process, it would serve as a prime example of nature-inspired solutions for sustainable urban development.

This project focuses on Bryophyta because of their limited numbers in the urban environment, and knowledge gaps in ecological understanding. Thus, this research holds a lot of promise to fill research gaps and the potential for enriching urban environments with more ecosystem services related to the hydrological cycle. The underlying line of thought could be applied to other species or whole ecosystems. the line of thought is: What can we learn from ecosystems to improve human-made systems?
This PhD will thus contribute to Eco-mimicry, an approach that uses natural systems as a model to redesign the systems in the built environment (Göker & Tuna, 2017). The research steps taken take an almost case study approach to make a framework that is based on empirical data and input from a specific context. To aid in sustainable urban development for the specific context this PhD will seek to engage the municipality of Utrecht as a partner, for input, feedback, and permission.

Research gap 1:
Most studies examining moss ecosystem services have relied on observational rather than experimental methodologies, restricting our ability to establish causal relationships between mosses and ecosystem services. The inherent complexity of natural systems has limited our understanding to correlations, leaving unanswered questions regarding the specific contributions of Bryophyta to ecosystem service generation across various habitats and climatic conditions. Addressing this gap requires a more balanced approach integrating both field observations and controlled laboratory experiments to elucidate causal relationships (Eldridge, et al., 2023). This PhD project aims to fill this void by focusing on clarifying the role of mosses in hydrological ecosystem service generation within highly managed ecosystems, particularly urban environments.

Research gap 2:
Our understanding of Bryophyta in urban environments remains incomplete, characterized by significant gaps in knowledge. Particularly, there is limited information regarding which moss species thrive in urban settings and the substrates that support their growth within urban landscapes (Żołnierz et al., 2022). This PhD research will address this gap by identifying moss species thriving in a Dutch city's urban environment. Furthermore, empirical research on Bryophyta ecosystem functioning and their relationship with ecosystem service production in urban areas is lacking as well as how it informs sustainable urban design (Kremer et al., 2016). This research will not only enhance our ecological understanding of moss but also explore how this knowledge can inform sustainable urban design.

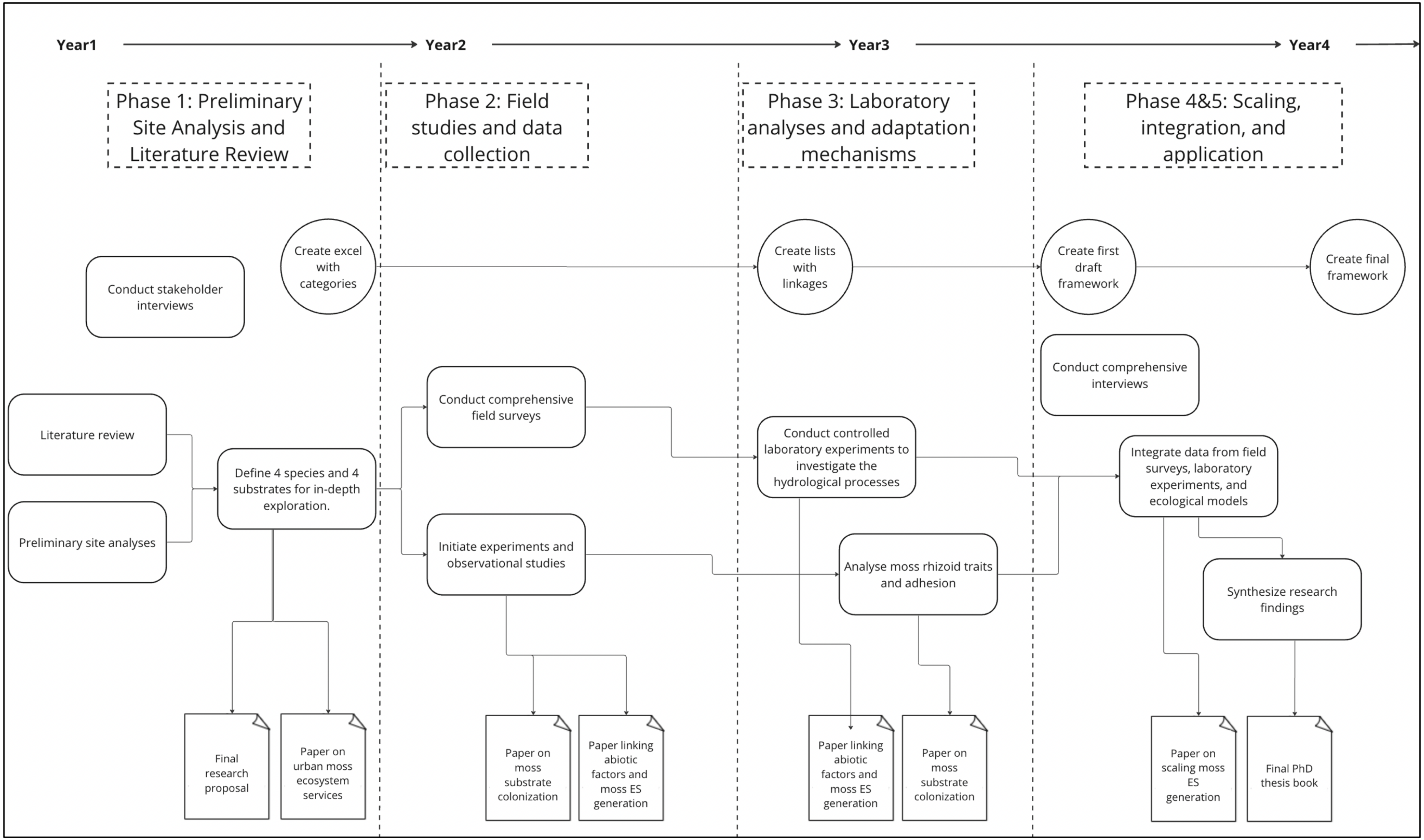
Research gap 3:
Research into system-level biomimicry in the built environment is severely limited, with almost no studies focusing on the functions and processes that underpin ecosystem service generation. Hayes, Desha & Gibbs (2019)& Hayes et al. (2020), advocate for scientists to develop the theoretical foundations for biomimicry in built-environment design to advance this field.
This PhD research will contribute to bridging this gap by exploring the theoretical underpinnings of biomimicry in the context of urban design and development.

Research gap 4:
There is a pressing need to bridge the gap between small-scale moss systems and services and their implications at larger scales, as well as vice versa. This requires the exploration of methods for extrapolating findings from localized studies to broader urban contexts (Göker & Tuna, 2017). Additionally, understanding which ecological information and concepts are relevant to urban designers to better comprehend ecosystem functioning and promote ecosystem service generation is essential (Blanco et al., 2021). Chayaamor-Heil (2023), adds that more research is needed on how to incorporate biological and other scientific knowledge into the design practice, including how to incorporate it into the urban context. This research will contribute to filling this gap by investigating how biological and scientific knowledge can be incorporated into urban design practices, particularly within the urban context.

<u>**Following the research gaps, the central question that will be researched in this PhD is:**</u>
How can systematic (experimental) studies on bryophytes in urban environments contribute to understanding their role in hydrological ecosystem services generation and inform decision-making for sustainable urban design strategies?

Approach

Research trajectory overview



Research trajectory explanation

Phase 1: Preliminary site analysis and literature review

A1. What specific ecological roles do bryophytes play within their ecosystems, and how do these roles contribute to the functioning and stability of natural habitats?

Moss from three key Dutch model ecosystems will be assessed: Peatland, dune forests, and willow forest (Janssen et al., 2007). The most abundant Bryophyta species will be used as a starting point and to compare with the species later: *Brachythecium rutabulum, Bryum argenteum, and Ceratodon purpureus* (IVN, 2022).

A2. How do bryophytes fulfil their ecological roles, in their ecosystems?

Extensive literature research into bryophyte ecology (Dutch & English), using sites such as Web of Science and ScienceDirect. An Excel sheet will be used to save the relevant literature found with the search term. There will also be a column to describe the similarities and differences between mosses in the different types of ecosystems in the Netherlands. The found processes will be categorized into general ecosystem processes, feedback loops and key points derived from the Millennium Ecosystem Assessment (2005) as a reference for the Ecomimicry framework.

B1. What are the root causes of flooding in the city of Utrecht?

A literature study both in English and Dutch will be performed, alongside interviews with key actors in the urban development sector of Utrecht.

B2. What ecosystem services can bryophytes provide within the urban environment?

Current examples of moss being used in cities for hydrological processes will be assessed. For example, water absorption mats (https://greencitysolutions.de/en/). These use cases could provide insight into their manner of thinking and way of translating biological knowledge to practical applications, which could inform the framework. Simultaneously, the traditional use of bryophytes and that of bryophytes in indigenous cultures worldwide will be researched with a literature review. The bryophyte ecology literature study will be continued with specific search terms to focus on ecosystem services in natural and urban systems.
The found processes will be categorized into general ecosystem processes, feedback loops and key points as a reference for the Ecomimicry framework.

C. What surfaces do bryophytes prefer in the urban environment?

Preliminary field studies will be performed in the Science Park and Utrecht. Both to determine suitable bryophyte species for controlled experiments and to establish 5 good research sites in the city and 3 at the Science Park.

The city and campus are to be divided into plots (10000 square meters) then random plots of the grid should be selected for the preliminary analysis. In this analysis, the large plots are subdivided into smaller quadrats of 50 x 50 m. Within these quadrats, a snake-like transect can be walked to assess the present moss species (Eldridge, Skinner & Entwisle, 2003).
The aim is to identify all mosses in the field within the transects. Doubtful or unknown species are to be collected in a non-destructive manner (for example images) for later identification in the laboratory.
To measure species in this field study the following formulas could be used (Adebiyi and Oyeyemi, 2013):

$$\%\, Occurence\ in\ all\ locations\ = \frac{Total\ number\ of\ each\ moss\ species\ found\ in\ all\ locations}{Total\ number\ of\ moss\ species\ found\ in\ all\ locations} \times\ 100$$

$$\%\, Occurence\ on\ all\ substrates = \frac{Total\ number\ of\ each\ moss\ species\ found\ on\ each\ substrate}{Total\ number\ of\ moss\ species\ found\ on\ all\ substrates} \times\ 100$$

$$\%\, Occurence\ on\ each\ substrate = \frac{Total\ number\ of\ each\ moss\ species\ found\ on\ each\ substrate}{Total\ number\ of\ moss\ samples\ collected\ from\ each\ substrate} \times\ 100$$

This field survey aims to find the most occurring species and substrates colonized in the city of Utrecht. After this research has completed the 4 most prevalent species will be chosen for in vitro experimental studies. This will also be done for the 3 most prevalent natural surfaces and 3 artificial surfaces.

<u>This phase will be concluded with a final research proposal after roughly 6 months and potentially 1 research paper.</u>

Phase 2: Field studies and data collection

A. Are there differences in substrate colonization by the same bryophyte species?

Setting up a 6-month to 1-year monitor experiment for bryophyte colonization and growth dynamics in urban areas. The 8 selected sites will be used.

A controlled experiment for substrate colonization will be set up to monitor speed and species performance. The 3 different natural and human-made surfaces that are selected after the field study will be used: Expected are: wood, bare soil, natural rock, brick stone, concrete, and cement (Mamchur et al., 2021; Żołnierz, et al. 2022). All substrates will be used in an intact and ground version.
(Potentially perform a similar test with extra-terrestrial rock.)

Plastic trays (319 mm × 241 mm × 72 mm) with freely draining bases can be filled to a substrate depth of 4 cm. Moss samples can be prepared by soaking in distilled water and sieved to remove most impurities including soil and litter. When applying the moss to the substrate a mixture of Moss: water (1:2) should be used, where the hydrated mosses are blended (Perini et al., 2020). The mixtures are to be weighed first to make sure all the samples have the same starting weight. Then they are placed with a spatula or applied with a brush to obtain a spot (about 1 mm thick and 5 × 5 cm wide) on the surfaces of the substrates (Nagase et al., 2023). An optimum range for temperature should be between 15-20°C, water should be sprayed every 2 days (Bu et al., 2015). Air humidity should be approximately 78% to mimic the average humidity in the Netherlands (KNMI, 2023).

The surface covered by mosses can be analysed using high-resolution photographs taken with a digital camera at a 100 cm distance. These are to be taken weekly for each sample (minimum 72ppi or px). To compare the surface covered by each sample, ImageJ software can be used, which allows quantifying the coverage percentage of moss for the whole image. Or can be done using the R package pixel classer, which can analyse the different pixel colours. The pictures were cropped to remain only inside of tray (Nagase et al., 2023). One-way ANOVA with Tukey post-hoc test can be used to evaluate significant differences among the selected moss mixture and substrates (Perini et al., 2020).

The combination of chosen methods can serve well as an initial study. Other factors such as nutrient content and water-holding capacity can be analysed in future research.

B. What factors limit or facilitate the growth and establishment of Bryophyta in urban settings, and how do these factors influence their ability to deliver hydrological ecosystem services?

Set up first site and laboratory experiments that evaluate Bryophyta under different abiotic conditions. Making use of climatic sensors: temperature, pH, moisture, light intensity. In the lab, each tray will receive a different treatment, with one control group per species.
Simultaneously set up hydrological measurements of the moss and environment. Microclimate monitoring in the field can be done using iButton® (DS1923 Hygrochron Logger) devices to monitor the microclimate differences between areas with and without moss cover (Jang & Viles, 2022). In the lab, iButton® devices can be covered with moss and some left bare to compare the moisture data.

<u>This phase will be concluded with 2 chapters and 2 potential paper publications.</u>

Phase 3: Laboratory analyses and adaptation mechanisms

A. Does Bryophyta hydrological regulation change in response to urban factors?

For a period of up to 6 months, the research sites will be monitored again. For this research, the Bryophyte Ellenberg values as adapted by Hill et al (2007), can be taken and supplemented with Dutch urban context factors. The urban indicators that will be assessed are temperature (spikes in particular), acidity and NH_3 + NO_2 concentration (Fojcik et al., 2015; Harmens et al., 2011). The research sites must be monitored twice a month for at least six months. Where the Ellenberg values for each site are logged manually and then related to the present species, environmental values by the KNMI, and other sites (Hill et al., 2007). In these monitoring rounds, moss and atmospheric water content shall also be measured, using iButton® (DS1923 Hygrochron Logger) or similar equipment and be related to precipitation.

During the same 6 months, a controlled comparison experiment will be set up in the laboratory. Where the species shall be exposed to the urban stressors of temperature, acidity and NH_3 + NO_2, and with control groups per species. The same Ellenberg value assessment and hydrology assessments shall be performed in the lab. Additionally, water holding will be evaluated. Each month a sample will be taken from the groups. First, they are weighed right after being obtained. Next, they shall be immersed in water for 24h where after removal held in the air for max 5 minutes and weighed. Lastly, the samples will be dried in an oven at 65 ℃ for 48h or until constant weight to obtain the dry weight of the samples (Hu et al., 2023).
The data between species in the controlled experiment and study sites can then be compared.

B. How do moss rhizoid traits enable certain moss species to grow on different substrates and at different angles?

Some papers touched upon similar research required for answering this research question. However, no paper provided a specific method, therefore I combined the methods of the closest studies. We need this research because it could prove very important for increasing moss abundance as well as understanding how their adhesion aids them in generating ecosystem services. Rhizoid analysis can help to identify Bryophyta traits, which can be linked to moss and ecosystem functioning (2021b).

Controlled laboratory experiments with the previously chosen substrates will be carried out to explore rhizoid dynamics to angles and whether their strategy for adhesion changes. The moss species will be grown in 4 different angles: control (horizontal), tilted (45 degrees), tilted (70 degrees), and vertical (90 degrees). Each replicate 5 x 5 cm of the same material can be glued to a larger panel of 30 x 30 cm. The materials can also be alternated between covered and uncovered with gauze. Application of moss on the materials should be done by dipping a brush in the mixture and gently spreading it out over the sample. Each sample should be sprayed every 1-2 days, once a day with 10 ml of deionized water (Perini et al., 2020). After 4-, 5- and 6-months samples will be taken for analysis.

Physiological analysis of the rhizoid system architecture, rhizoid morphology and rhizoid anatomy can be analysed either manually with a microscope, or digitally with image analysis. And this technique shall be adapted from plant root trait analysis from Freschet et al (2021a). Traits like total length, diameter, specific length, etc. can be explored.
The similarities and differences per species and substrates can be compared with statistical models and put in various comparative figures.
Previous research has made me familiar with plant root trait analysis, therefore I feel confident in applying similar principles to moss rhizoids and uncovering important relationships.

<u>This phase will be concluded with 1 chapter and 2 potential paper publications.</u>

Phase 4 & 5 Scaling, integration, and application

A. How do the beneficial functions and ecological roles of Bryophyta observed at a microscale (for example, high local water capture) translate into cumulative effects when scaled up to larger urban blocks or citywide areas?

To assess the impact of ecosystem services a relative interaction intensity index (RII) could be used.
The index compares the differences between Bryophyta and bare surface, with RII = (Xo – Xb) ⁄ (Xo + Xb).
Where X is the value of a specific attribute, and Xo and Xb represent values beneath the organisms and the bare surface, respectively. Positive RII values indicate an increase in the value of ecosystem services beneath mosses compared with bare soils and vice versa (Eldridge, et al., 2023). For this PhD research, the attributes to be analysed shall be water holding capacity, water runoff and surface temperature.

Ecosystem health indicators can be modified for the specific context. The mean Bryophyta Ellenberg value (Hill et al., 2007), for each habitat or climate attribute per square meter can be calculated for the species sites. To assess trends in time the data can be analysed using a Linear Mixed Model in R with nlme, using month as the sole fixed factor. Trends for mean monthly values can be fitted with Generalised Additive Models (GAMs) using mgcv. The use of attribute values can provide a direct link to changes within ecosystems (Pakeman et al., 2019).

B. What are the potential cascading effects and interactions of Bryophyta-based interventions, considering their integration from smaller-scale ecosystem functions to larger urban landscapes, and how might these effects contribute to overall urban sustainability and resilience?

To try and answer this question different causality models shall be tested with the data, such as; structural equation modelling (SEM), Structural causal modelling (SCM), Graphical-causal-model framework, and the potential-outcome framework (Arif & MacNeil, 2023; Runge, 2023).
Test the recent macroecological scaling methods devised by Wickman, Litchman & Klausmeier (2024). For compatibility with Bryophyta.

This research phase will also see the start of lists, categorization, and visualizations for making connections between the studied functions and effects.

C. What do urban decision-makers need to tackle urban flooding in Utrecht?

In-depth stakeholder interviews will be performed with members of the urban planning team for the city of Utrecht, policymakers and urban planners at the University of Utrecht.

To aid the interviewees with the concept a comparison between an ecosystem and the city through the form of abstractions, examples, and an early version of the proposed framework (see Figure 2.1)shall be made to supplement the interview.

D. How can insights derived from understanding moss ecological functions serve as a foundation for developing a practical ecomimicry framework?

A general definition of a framework is "a system of rules, ideas, or beliefs that is used to plan or decide something" (Hernandez-Santin et al., 2022). In both top-down and bottom-up mechanisms, frameworks can play a vital role in synthesizing and communicating ideas among scholars in a field. Frameworks can make day-to-day science easier. As they can guide the design of new empirical research through the indication of core concepts and relationships. Frameworks also aid in communicating findings and advancements through a common language (McGinnis and Ostrom 2014a; Ban and Cox 2017). As such, frameworks guide synthesis research by providing core sets of concepts and relationships (Partelow, 2023). In the field of Biomimicry, there exist a few early frameworks. But thanks to its novelty, there is still a lot of room for discovery and further development of frameworks. Therefore, this PhD thesis sets out to create a novel framework for Ecomimicry to aid future advancements in the field and guide relevant decision-makers. The steps for how the framework shall be built up are adapted from Jabareen (2009).

Stage 1: Mapping the selected data sources. This is done in earlier phases of the PhD

Stage 2: Categorizing the data. Found data should be categorized based on biomimicry and systems thinking principles.

Stage 3: Identifying and naming concepts. The result should be a list of numerous competing and sometimes contradictory concepts.

Stage 4: Deconstructing and categorizing the concepts. This stage aims to deconstruct each concept; to identify its main attributes, characteristics, assumptions, and role. The result of this phase is a table that includes four columns: First the names of the concepts, a description of each concept with the role, characteristics & attributes of the concept, and lastly the larger systemic place & analogies of the concept (abstraction).

Stage 5: Integrating concepts. In this stage, similar concepts will be grouped into a new concept or linked to concepts it has the most synergy with. This phase reduces the number of concepts drastically and allows for a reasonable number of concepts moving forward.

Stage 6: Synthesis and resynthesis. The first conceptual framework will be made. Which will be tested and evaluated by multiple relevant actors. This shall then be used to make the first version of the practical framework.

Stage 7: Validating and rethinking the framework. First, the practical framework shall be evaluated and presented to 'outsiders' of different fields and levels of interest. Both for validation and to receive feedback. This should then lead to another round of iteration for the conceptual framework. Which will be subjugated to discussion from experts in different fields. This shall lead to the next iteration of the practical framework, which shall be subjugated to a final round of feedback from a broad range of professionals. Which shall inform the final iteration of the practical framework for the PhD thesis.

The final framework should have a few key elements. Firstly, empirical generalization. The empirical observations both from experiments and literature should be used to infer observations as representative of broader phenomena. Secondly, there should be a focus on applicability. The empirical observations should inform what is important to observe, for example, a list of variables or relationships to focus on (Partelow, 2023). The framework should enable knowledge to be built up and collected within and between scientific fields by providing common languages and concepts. It is important in the end to explain how the framework came to be and the background of the researcher(s) in question. Next to this the purpose and intended use of the framework should be clearly stated (Ban and Cox 2017; Partelow, 2023).

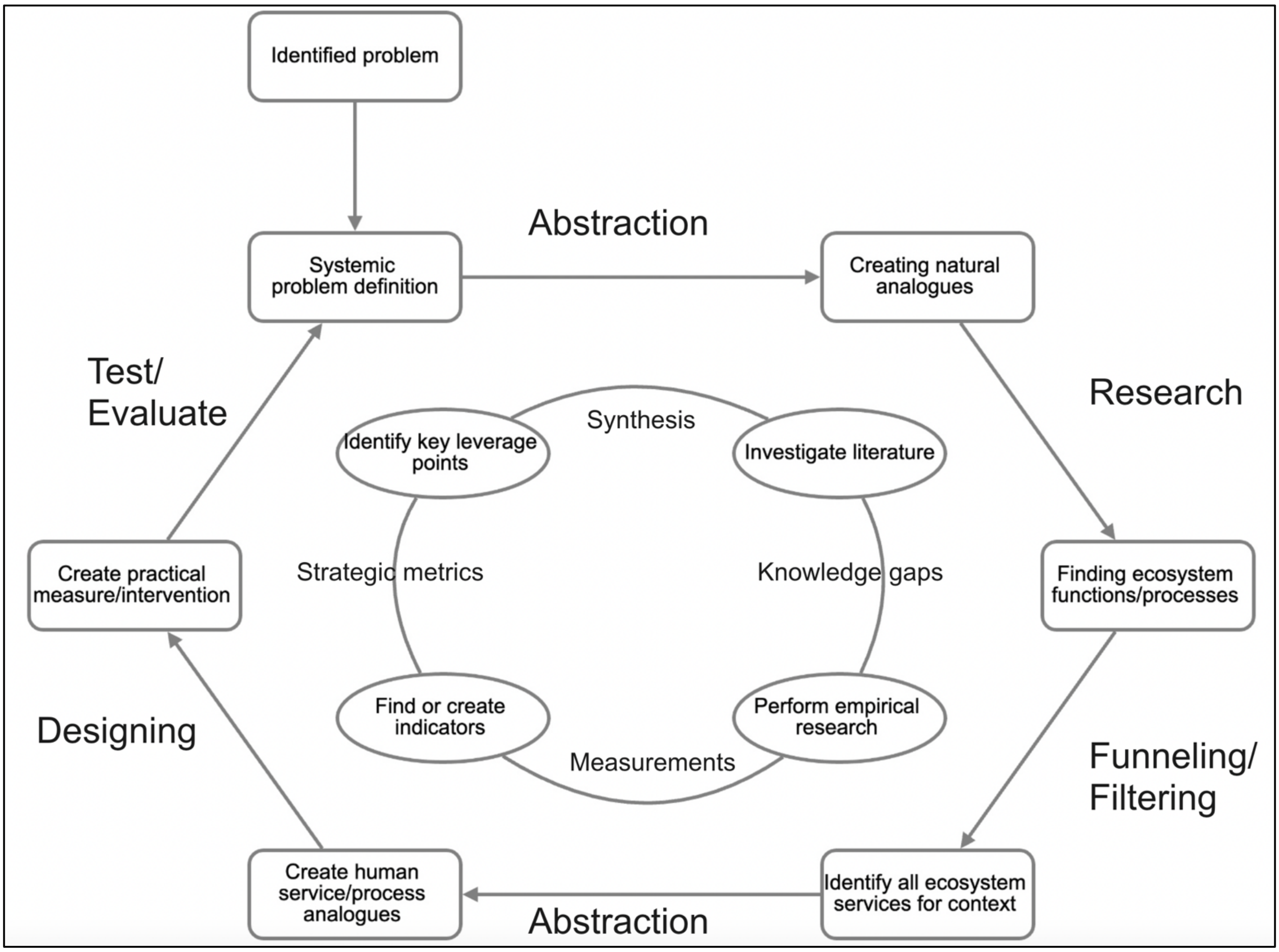


Figure 2.1, Preliminary Ecomimicry model, as the PhD goes along this model shall be updated and adjusted.

This model (see Figure 2.1) shall also be used in the case study scenario of increased precipitation in the city. Potential example steps: Moss can hold up to 20 times their weight in water ->
So, if a part of the city would be covered by moss this could mean a lot of capture ->
When you take an abstraction for this it could mean that you do not want very large, centralised water storage units, but a lot of smaller water capture measures spread out that together could capture a lot of rainwater.

<u>This phase shall also result in the final chapter, a potential paper publication, and the finalization of the PhD thesis.</u>

Feasibility and Risk assessment

Moss growth could be slow which could affect the timeline of certain experiments. The Ecology & Biodiversity department has experience with ecological research and plant cultivation. Meaning there is a lot of knowledge that can be drawn from. Additionally, some literature discusses speeding up moss growth. Moss is generally not sped up in its growth process. A potential change of species or growth conditions for known successful experimentally grown species can be chosen. For the moss in the research sites, no interference shall be done to the 'natural' situation to keep the results as close to normal for the urban context.

Although conceptual framework analysis has its limitations - such as the fact that I will have my background and conceptions of functions, which can lead to frameworks that would be different than somewhere else. Luckily framework development is based on flexible conceptual terms rather than rigid theoretical variables and causal relations. This makes it possible to modify the frameworks. Conceptual frameworks can be reconceptualized and modified according to the evolution of the phenomenon in question (Jabareen, 2009). This can be done even after the PhD has been completed. Also, multiple rounds and a broad range of people who will be asked for feedback can help limit my own biases.

Suppose the first phases find that a new framework will be too time-consuming or challenging to be completed based solely on the PhD research. In that case, the most closely related existing framework can be taken as a basis and modified with the research results.

There will be a mixture of field assessments, laboratory experiments and creative out-of-the-box thinking about results. While challenging to combine these components, my unique background and previous research experiences are well suited to spearhead this innovative PhD research project. However, to ensure a good result multiple experts from different fields shall be consulted. The team of promoters shall also be as interdisciplinary as possible.

Scientific and societal impact

Phase 1: This phase will contribute to improving understanding of the role Bryophyta have in hydrological ecosystem services. The literature research could also help to increase the appreciation and valuation of indigenous and more forgotten historical relations with moss. On a local scale, this phase will help to increase the database of moss species for Utrecht and the Utrecht Science Park.

Phase 2: This phase together with the initial field research from phase one can serve to further develop the in-depth but easy-to-use moss monitor method. This method could improve citizen science engagement. This phase could even lead to the suggestion of a local and national moss counting day or moss spotting day, in a similar trend to birds, bees, butterflies, etc. All to increase awareness about moss, while increasing the knowledge database of moss species that thrive in the Dutch urban environment.

Phase 3: The results of this phase will increase the understanding of Bryophyta functionality and hydrological ecosystem services generation in the urban environment. While also diving deeper into moss rhizoid analysis. This phase lends itself particularly well to the synthesis of multiple novel research papers. As both the ecosystem services generation and adaptation of plant root trait analysis for rhizoid analysis appear as unfilled knowledge gaps. The knowledge obtained in this phase can also contribute to a larger extent to improving the colonization and growth of mosses in the built environment making better use of their ecosystem services.

Phase 4 & 5: System-level biomimicry in the built environment Bryophytes could prove to add and improve very valuable ecosystem services in urban areas. Besides this, the lessons we can learn from them could improve our understanding of ecosystems as well as how to look at human-made urban systems. To identify and tackle challenges in a more effective, sustainable, and systemic manner. Besides the systemic perspective for biomimicry could also further that field and hopefully add another practical tool for the toolbox that could be used not only by scientists but also by other professionals.
The biggest impact from these phases would be a new practical artefact (see Figure 4.1) based on scientific research that can contribute to solving urban water problems and beyond, adapted from Wieringa (2016).

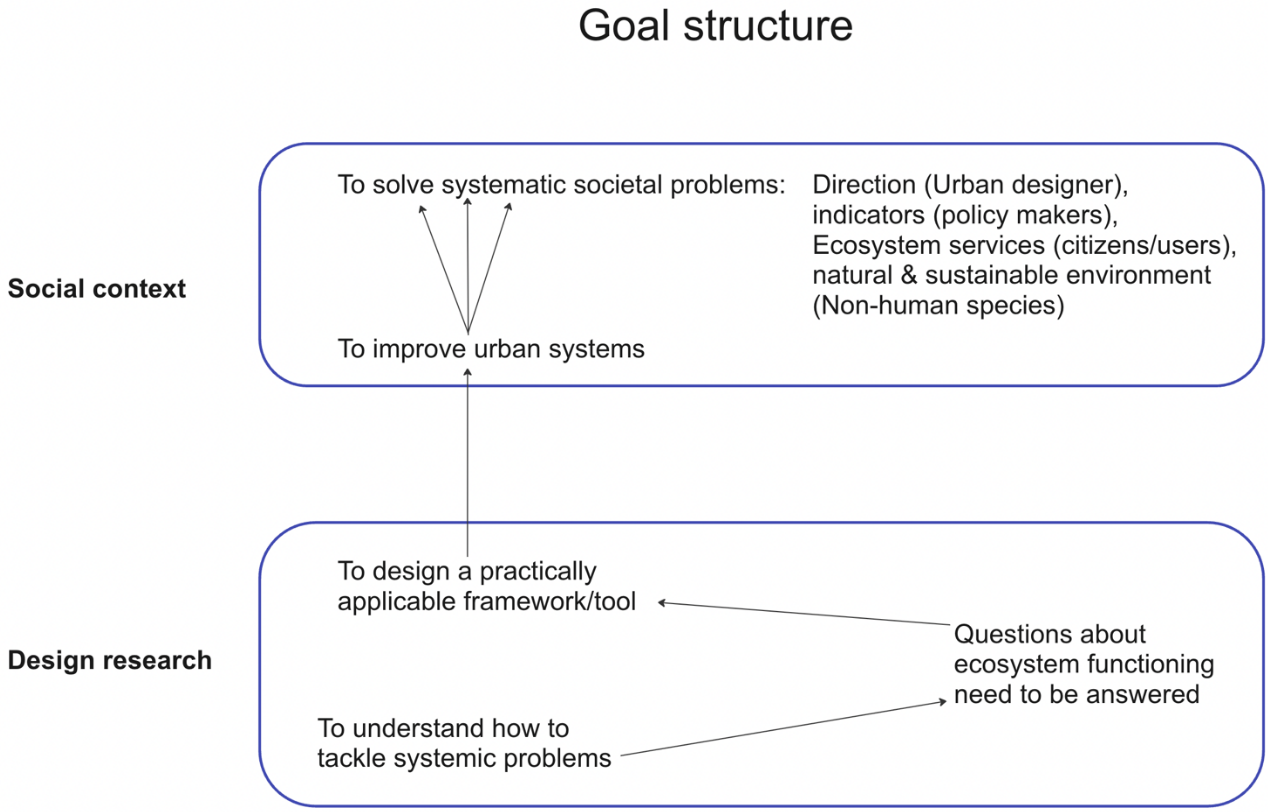


Figure 4.1, Goal structure adapted from Wieringa, R. (2016).

Ethical considerations

In researching bryophytes in the lab, within university campuses and urban locations, several ethical considerations should be considered to ensure responsible and ethical practices. My ethical concerns include:

- Invasive Species and Introduction:
    - There should be ethical considerations when introducing bryophyte species into new areas for experimental purposes. As well as be careful not to let species from laboratory settings escape and become invasive. To mitigate this, I want to work only with indigenous Dutch bryophyte species.

- Respect for the Natural Environment:
    - Ensure minimal disturbance to the natural environment and biodiversity while conducting site analyses and experiments.

    - Use environmentally friendly materials and practices in experimental setups to minimize any potential negative impacts on the surroundings.

    - Cleaning surfaces should happen in ecologically responsible ways.

    - Sourcing bryophyte specimens involves considerations about responsible collection practices. Overharvesting or depleting populations in natural habitats should be avoided entirely.

    - Sample collection should be done in a non-destructive manner.

    - Some bryophyte species thrive in fragile or environmentally sensitive habitats. Conducting research in such areas may require extra caution.

    - The exact location of rare or endangered bryophyte species may have to be avoided to prevent over-collection or habitat destruction by outside parties.

- Informed Consent and Permissions:
    - Necessary permissions and clearances from relevant authorities should be obtained before researching private or public properties.

    - The privacy and confidentiality of sensitive information should be safeguarded. Steps need to be taken to ensure proper data anonymization and secure storage of sensitive information.

- Equitable Participation and Acknowledgment:
    - Ensure equitable participation and recognition of all contributors, including volunteers, students, or community members involved in data collection or research activities. This is done by appropriate acknowledgement or authorship to individuals or groups who significantly contribute to the research.

- Respect for Cultural and Indigenous Knowledge:
    - Respect and acknowledge indigenous knowledge and cultural practices related to bryophytes or the studied ecosystems, seeking appropriate consultation and collaboration with local communities when necessary.

- Communication of results:
    - It is important to consider that advocating for a specific view and or methodology will reflect mainly my thoughts and ideas. In the long term, this can lead to results being too close-minded and not considering unforeseen circumstances. Therefore, it is important to see the results as a part of a larger puzzle and the eventual framework not as a static and stand-alone use.

Literature

1. Adebiyi, A. O., & Oyeyemi, S. D. (2013). Distribution of mosses in Ekiti State, Nigeria. New York Sci Journal, 6(6), 23-25.

2. Anderson, M., Lambrinos, J., & Schroll, E. (2010). The potential value of mosses for stormwater management in urban environments. Urban ecosystems, 13, 319-332.

3. Arif, S., & MacNeil, M. A. (2023). Applying the structural causal model framework for observational causal inference in ecology. Ecological Monographs, 93(1), e1554.

4. Bahuguna, Y. M., Gairola, S., Semwal, D. P., Uniyal, P. L., & Bhatt, A. B. (2013). Bryophytes and ecosystem. Biodiversity of lower plants, 2013, 279-296.

5. Blanco, E., Pedersen Zari, M., Raskin, K., & Clergeau, P. (2021). Urban ecosystem-level biomimicry and regenerative design: Linking ecosystem functioning and urban built environments. Sustainability, 13(1), 404.

6. Blok, V., & Gremmen, B. (2016). Ecological innovation: Biomimicry as a new way of thinking and acting ecologically. Journal of Agricultural and Environmental Ethics, 29, 203-217.

7. Bu, C., Zhang, K., Zhang, C., & Wu, S. (2015). Key factors influencing rapid development of potentially dune-stabilizing moss-dominated crusts. PLoS One, 10(7), e0134447.

8. Chayaamor-Heil, N. (2023). From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges. Encyclopedia, 3(1), 202-223.

9. Cristiano, S., Zucaro, A., Liu, G., Ulgiati, S., & Gonella, F. (2020). On the systemic features of urban systems. A look at material flows and cultural dimensions to address post-growth resilience and sustainability. Frontiers in Sustainable Cities, 2, 12.

10. Cooper, R. (2019). Design research–Its 50-year transformation. Design Studies, 65, 6-17.

11. Dai, L., Wörner, R., & van Rijswick, H. F. (2017). Rainproof cities in the Netherlands: Approaches in Dutch water governance to climate-adaptive urban planning. International Journal of Water Resources Development, 34(4), 652-674.

12. Duncan, R. P., Clemants, S. E., Corlett, R. T., Hahs, A. K., McCarthy, M. A., McDonnell, M. J., ... & Williams, N. S. (2011). Plant traits and extinction in urban areas: a meta-analysis of 11 cities. Global ecology and biogeography, 20(4), 509-519.

13. Eales, R., White, O., Saudaskis, R., Kolarič, Š., Heeckt, C., Rode, P., & Pereira Martins, I. (2021). Urban sustainability in Europe: Avenues for change.

14. Eldridge, D. J., Guirado, E., Reich, P. B., Ochoa-Hueso, R., Berdugo, M., Sáez-Sandino, T., ... & Delgado-Baquerizo, M. (2023). The global contribution of soil mosses to ecosystem services. Nature Geoscience, 1-9.

15. Eldridge, D., Skinner, S., & Entwisle, T. J. (2003). Survey guidelines for non-vascular plants. A report produced under the NSW Biodiversity Strategy. Botanic Gardens Trust, Sydney.

16. Francesch-Huidobro, M., Dabrowski, M., Tai, Y., Chan, F., & Stead, D. (2017). Governance challenges of flood-prone delta cities: Integrating flood risk management and climate change in spatial planning. Progress in planning, 114, 1-27.

17. Freschet, G. T., Pagès, L., Iversen, C. M., Comas, L. H., Rewald, B., Roumet, C., ... & McCormack, M. L. (2021a). A starting guide to root ecology: strengthening ecological concepts and standardising root classification, sampling, processing and trait measurements. New Phytologist, 232(3), 973-1122.

18. Freschet, G. T., Roumet, C., Comas, L. H., Weemstra, M., Bengough, A. G., Rewald, B., ... & Stokes, A. (2021b). Root traits as drivers of plant and ecosystem functioning: current understanding, pitfalls and future research needs. New Phytologist, 232(3), 1123-1158.

19. Fojcik, B., Chruścińska, M., Nadgórska-Socha, A., & Stebel, A. (2015). Determinants of occurrence of epiphytic mosses in the urban environment; a case study from Katowice city (S Poland). *Acta Musei Silesiae, Scientiae Naturales*, *64*(3), 275-286.

20. Göker, F. P., & Tuna, S. A. (2017). The Eco-Mimicry Approach Towards Cityscape Design and Examples in the World. In *2th International Conference on Civil and Environment Engineering. May* (pp. 8-10).

21. Harmens, H., Norris, D. A., Cooper, D. M., Mills, G., Steinnes, E., Kubin, E., ... & Zechmeister, H. G. (2011). Nitrogen concentrations in mosses indicate the spatial distribution of atmospheric nitrogen deposition in Europe. Environmental Pollution, 159(10), 2852-2860.

22. Hayes, S., Desha, C., & Baumeister, D. (2020). Learning from nature–Biomimicry innovation to support infrastructure sustainability and resilience. Technological Forecasting and Social Change, 161, 120287.

23. Hayes, S., Desha, C., & Gibbs, M. (2019). Findings of case-study analysis: System-Level biomimicry in built-environment design. Biomimetics, 4(4), 73.

24. Haynes, A., Popek, R., Boles, M., Paton-Walsh, C., & Robinson, S. A. (2019). Roadside moss turfs in South East Australia capture more particulate matter along an urban gradient than a common native tree species. Atmosphere, 10(4), 224.

25. Hernandez-Santin, C., Amati, M., Bekessy, S., & Desha, C. (2022). A Review of Existing Ecological Design Frameworks Enabling Biodiversity Inclusive Design. Urban Science, 6(4), 95.

26. Hill, M. O., Preston, C. D., Bosanquet, S. D. S., & Roy, D. B. (2007). BRYOATT: attributes of British and Irish mosses, liverworts and hornworts. Centre for Ecology and Hydrology.

27. Hu, X., Gao, Z., Li, X. Y., Wang, R. Z., & Wang, Y. M. (2023). Structural characteristics of the moss (bryophyte) layer and its underlying soil structure and water retention characteristics. *Plant and Soil*, 1-19.

28. IVN. (2022). Mossen - Gooi en omstreken. https://www.ivn.nl/afdeling/gooi-en-omstreken/mossen/

29. Jabareen, Y. (2009). Building a conceptual framework: philosophy, definitions, and procedure. International journal of qualitative methods, 8(4), 49-62.

30. Jackson, T. A. (1971). Study of the ecology of pioneer lichens, mosses, and algae on recent Hawaiian lava flows.

31. -, K., & Viles, H. (2022). Moisture interactions between mosses and their underlying stone substrates. Studies in Conservation, 67(8), 532-544.

32. Janssen, J. A. M., Stumpel, A. H. P., Bijlsma, R. J., Hennekens, S. M., Keizer-Sedlakova, I., Kuiters, A. T., ... & Siebel, H. N. (2007). Internationaal belang van de nationale natuur: ecosystemen, vaatplanten, mossen, zoogdieren, reptielen, amfibieën en vissen.

33. Jatsch, A. S., Jacobs, S., Wommer, K., & Wanieck, K. (2023). Biomimetics for Sustainable Developments—A Literature Overview of Trends. Biomimetics, 8(3), 304.

34. KNMI - Groter natuurbrandgevaar door dalende luchtvochtigheid. (2023). https://www.knmi.nl/over-het-knmi/nieuws/groter-natuurbrandgevaar-door-dalende-luchtvochtigheid#:~:text=In%20Nederland%20is%20de%20relatieve,figuur%201%2C%20zwarte%20lijn).

35. Kremer, P., Hamstead, Z., Haase, D., McPhearson, T., Frantzeskaki, N., Andersson, E., ... & Elmqvist, T. (2016). Key insights for the future of urban ecosystem services research. Ecology and Society, 21(2).

36. Landrum, N. E., & Mead, T. (2022). Sustainability in the Biom. In Bionics and Sustainable Design (pp. 1-15). Singapore: Springer Nature Singapore.

37. Mamchur, Z., drach, Y., ragulina, M., prytula, S., & antonyak, H. (2021). Substrate groups of bryophytes in the territory of the znesinnya regional landscape park (lviv, ukraine). *Contributii Botanice*, (56).

38. Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: Synthesis.* Island Press, Washington, DC.

39. Nagase, A., Katagiri, T., & Lundholm, J. (2023). Investigation of moss species selection and substrate for extensive green roofs. Ecological Engineering, 189, 106899.

40. Pakeman, R. J., Brooker, R. W., O'Brien, D., & Genney, D. (2019). Using species records and ecological attributes of bryophytes to develop an ecosystem health indicator. Ecological Indicators, 104, 127-136.

41. Partelow, S. (2023). What is a framework? Understanding their purpose, value, development, and use. Journal of Environmental Studies and Sciences, 1-10.

42. Perini, K., Castellari, P., Giachetta, A., Turcato, C., & Roccotiello, E. (2020). Experiencing innovative biomaterials for buildings: Potentialities of mosses. Building and Environment, 172, 106708.

43. Richter, S., Schuütze, P., & Bruelheide, H. (2009). Modelling epiphytic bryophyte vegetation in an urban landscape. Journal of bryology, 31(3).

44. Runge, J. (2023). Modern causal inference approaches to investigate biodiversity-ecosystem functioning relationships. nature communications, 14(1), 1917.

45. Thielen, S. M., Gall, C., Ebner, M., Nebel, M., Scholten, T., & Seitz, S. (2021). Water's path from moss to soil: A multi-methodological study on water absorption and evaporation of soil-moss combinations. Journal of Hydrology and Hydromechanics, 69(4), 421-435.

46. Wickman, J., Litchman, E., & Klausmeier, C. A. (2024). Eco-evolutionary emergence of macroecological scaling in plankton communities. *Science*, *383*(6684), 777-782.

47. Wieringa, R. (2016). Design science research methods and writing research papers.

48. Wolfram, M., Frantzeskaki, N., & Maschmeyer, S. (2016). Cities, systems and sustainability: Status and perspectives of research on urban transformations. Current Opinion in Environmental Sustainability, 22, 18-25.

49. Żołnierz, L., Fudali, E., & Szymanowski, M. (2022). Epiphytic Bryophytes in an Urban Landscape: Which Factors Determine Their Distribution, Species Richness, and Diversity? A Case Study in Wroclaw, Poland. International Journal of Environmental Research and Public Health, 19(10), 6274.