Tactical & Technological Growth:

Interdisciplinary Investigations of Biophilic Tactical Urbanism for Learning Environments

A dissertation presented to the Graduate Faculty of the University of Virginia in Candidacy for the Degree of Doctor of Philosophy in the Constructed Environment

James S. Barnes
PhD Candidate in the Constructed Environment
The University of Virginia
School of Architecture

Committee
Dr. Jenny Roe - Chair
Brad Cantrell
John Comazzi

The Dissertation Committee for James S. Barnes certifies that this is the approved version of the following dissertation:

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Committee:

Dr. Jenny Roe - Chair
Department of Urban & Environmental Planning
The University of Virginia

Prof. Brad Cantrell
Department of Landscape Architecture
The University of Virginia

Associate Dean & Prof. John Comazzi
Department of Architecture
The University of Virginia

Abstract

This dissertation investigated temporary, low-cost biodiversity interventions as an empirical methodological innovation. The concept of "temporary biodiversity" as a tool was explored through an interdisciplinary framework that integrated 1) technological, 2) ecological, and 3) human behavior research domains and culminated in a 1:1 scale, parametrically generated installation that was deployed in a U.S. public elementary schoolyard.

The drivers for this research were both theoretical and practical. First, biodiversity is undergoing a 6th mass extinction event globally. The complex interactions between biodiversity and the built environment in places like public schools–a critical space for engaging youth with nature–is poorly understood, from both ecological and socio-ecological perspectives. Equally important, public schools are often bereft of high quality, biodiverse-rich environments with implications for student education and overall well-being. Temporary biodiversity interventions were explored as a means to 1) generate new knowledge at the human / biodiversity / built environment nexus in public schools, and 2) serve as an applied "stepping-stone" strategy towards more biodiversity-integrated outdoor learning environments.

Temporary biodiversity interventions were theoretically framed through the term *Biophilic Tactical Urbanism* (BTU). BTU represented a novel intersection of tactical urbanism, biophilic design, and multispecies design concepts. Interdisciplinary, scaffolded research explored BTU through technological, ecological, and human behavior lenses. First, from a technological perspective, computational modeling of container-grown plant growth, performance, and aesthetic was conducted under architectural-inspired scenarios (slope, deflection, angled rotation, and agency). The indigenous "Three Sisters" polyculture co-planting

system (corn, beans, squash, and sunflowers) served as a model ecology system. Results revealed species-specific responses, directly influencing subsequent BTU designs in later research.

Second, the ecological impacts of a 1:1 scale, parametrically generated BTU intervention were assessed in an elementary school parking lot. This research focused on plant-insect interactions and micro-spatial heat island impacts. The results showed that greater plant species richness in BTU designs correlated with increased insect family richness, especially among bees, wasps, and ants. Furthermore, the BTU intervention significantly reduced surface parking lot temperatures, demonstrating its potential for urban heat mitigation.

Finally, a human subjects study, conducted in partnership with an elementary school art teacher through a co-design framework, examined the psycho-social impacts of the 1:1 scale BTU intervention on student classroom engagement and biodiversity perception through nature photography. Classroom engagement, measured through attention redirects, teacher evaluations, and classroom outputs (n=115), improved over a three-week period compared to a conventional indoor classroom. Analysis of student photographs revealed varying perceptions of biodiversity and associated affective caption content in the BTU outdoor classroom, along with age differences between three grade levels (n=201) on their photographic engagement with insects.

Overall, this dissertation explored an interdisciplinary applied research strategy for schoolyard greening towards biodiversity that integrated design, technology, and participatory processes, serving as a proof of concept for future, larger-scale research.

Acknowledgements

I would like to thank my PhD advisor and committee members who have guided me on this extraordinary journey over the past 5 years. For my field research at Keister Elementary - Brooke Imber, Superintendent Micheal Richards, and Principal Erin Young were invaluable. David Carr and T'ai Raulston at Blandy Experimental Farm were instrumental in providing financial and material resources (potting soil!) and their time over three years. Vivian Wong was very helpful in framing statistical analysis. Andrew Mondeschien and Tim Beatley provided key sounding boards at critical junctures. Shiqiao Li and Nana Last guided theoretical explorations early in this work. Adam Dalton, Addie Merlo, and Robin Xiao were wonderful student design assistants. Lastly, thanks to my fellow Constructed Environment PhD students for chiming in on the early stages of this work.

This research was generously supported by the UVA School of Architecture, Phipps Conservatory and Botanical Gardens, UVA's Blandy Experimental Farm and State Arboretum of Virginia, the UVA Sustainability's Equity and Environment Fund, the UVA Student Arts Council, the UVA Sustainable Food Collaborative, Harrisonburg City Public Works, Harrisonburg City Public Schools, and the Natural Garden in Harrisonburg.

The indigenous polyculture practice of the Three Sisters was incorporated into several aspects of this research. I respectively acknowledge and honor the myriad indigenous tribes past and present who have carried and nurtured this polyculture tradition through the eons, especially the Haudenosaunee and Mashpee Wampanoag tribes, whose traditions this research draws from, as well as the Monancan ancestral lands where the research occurred.

Mostly importantly, I owe immeasurable gratitude to Audrey Barnes, my partner for most things in my life, including many parts of this work, and for inspiring me to take the leap.

Dedication

I owe immense gratitude to my family for supporting me through this tremendous journey.

Sawyer, Ryka, Jolene, and Audrey – you are amazing, and I love you.

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Abbreviations

ANOVA: Analysis of variance statistical test

BTU: Biophilic Tactical Urbanism

H1, etc.: Hypothesis 1, etc.

T/t urbanism: Tactical/temporary urbanism

Glossary

Affect: The underlying psychological experience of feeling, emotion, attachment, or mood

Biodiversity: The variability of life on earth

Biophilic design: Creating good habitat for people as a biological organism in the modern built environment that advances people's health, fitness and wellbeing

Classroom engagement: A student or class's ability to pay attention and stay on task

Co-design: An approach to design attempting to actively involve stakeholders in the design process to help ensure the result meets their needs and is usable

Design computation: A design method that uses a combination of algorithms and parameters to solve design problems with advanced computer processing

Landscape ecology: The scientific study of how spatial patterns within a landscape, like the arrangement of different ecosystems, interact with and influence ecological processes. It can be described as the science of "landscape diversity"

Multispecies design: A design approach that considers other species and their interactions with humans. Closely related to the terms "living architecture", "more than human design", and biodiversity inclusive design

Parametric modeling: A design method that uses algorithms to create digital 3D models

Redirects: A teacher is actively guiding a student's attention away from an undesirable behavior or activity towards a more appropriate one

Species richness: The number of different species in a given area

Tactical/Temporary urbanism: An approach to neighborhood building and activation using short-term, low-cost and scalable interventions and policies

The Three Sisters: The indigenous American polyculture co-planting system of corn, beans, and squash, which often included sunflowers and other species

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Chapter 1: Introduction

Sympoiesis is a simple word; it means "making-with." Nothing makes itself; nothing is really autopoietic or self-organizing….. a word proper to complex, dynamic, responsive, situated, historical systems. It is a word for worlding-with, in company. (58)

(Haraway, 2016)

1.1 The Problem(s)

Globally, biodiversity is in decline across many ecosystem types and taxa of organisms (IPBES, 2019) and the built environment has an increasingly role in mitigating this trend (Lambert & Schell, 2023; Spotswood et al., 2021). Meanwhile, the lived experience of biodiversity is simultaneously in decline among many cultures (Soga & Gaston, 2016). These conjoined issues present a fundamental challenge for humanity and non-human life; biodiversity underpins most ecosystem services (Haines-Young & Potschin, 2010). A feedback loop could emerge where decreases in biodiversity drive societies to value it less, and vice versa (Soga et al., 2023). Childhood and the spaces of formal education represent a critical venue for biodiversity engagement from an environmental education perspective (Børresen et al., 2023; Lindemann-Matthies, 2002; R. L. White et al., 2018; Wolff & Skarstein, 2020). Yet from a theoretical perspective our understanding of how children engage with and perceive biodiversity in the context of formal learning environments (Navarro-perez & Tidball, 2012), as well as how biodiversity affects child well-being, has not been clearly illuminated (Davis et al., 2025).

Equally, U.S. K-12 public schools, the space of education for most American children, often do not incorporate substantive biodiversity into their design and management (Barnes & Barnes, Audrey, 2023; Schulman & Peters, 2008). Numerous initiatives to green schoolyards do exist, but the gap between ideal and practice is large, especially from an equity perspective, owing to resource limitations, information gaps, and stakeholder buy-in (Stevenson et al., 2020). Design-based intervention strategies that link application with empirical research across multiple relevant domains to biodiversity, including ecology, technology, and human behavior could provide novel catalysts in the unique spatial and programmatic context of public schools, where both top-down and bottom-up approaches are needed for systematic change.

1.2 Aim of Dissertation

> *There are no cheap tickets to mastery. You have to work hard at it, whether that means rigorously analyzing a system or rigorously casting off your own paradigms and throwing yourself into the humility of Not Knowing. In the end, it seems that mastery has less to do with pushing leverage points than it does with strategically, profoundly, madly letting go.*
>
> Donella Meadows, *Leverage Points: Places to Intervene in a System* (Meadows, 1997)

In response to the challenges listed in the above section, the primary objective of this dissertation was to research and develop the concept of *temporary biodiversity interventions* as a novel method for knowledge production and application, particularly in the context of children's learning environments. What could we learn from "putting nature on wheels" in the context of U.S. K-5 public education? Rather than focus on one specific knowledge domain to explore this broad question, this work investigated temporary biodiversity interventions through three interconnected domains: technological, ecological, and human behavior (Fig. 1). Specifically:

1. [Technological Assemblage] How does the horticulture of temporary biodiversity interventions respond to the built environment, and could this be modeled parametrically?

2. [Ecological Impacts] What impact do 1:1 temporary biodiversity interventions have on the broader ecology of the surrounding environment, including insects and heat?

3. [Human Behavior Impacts] How do students engage with and perceive 1:1 temporary biodiversity interventions in the context of K-5 formal education?

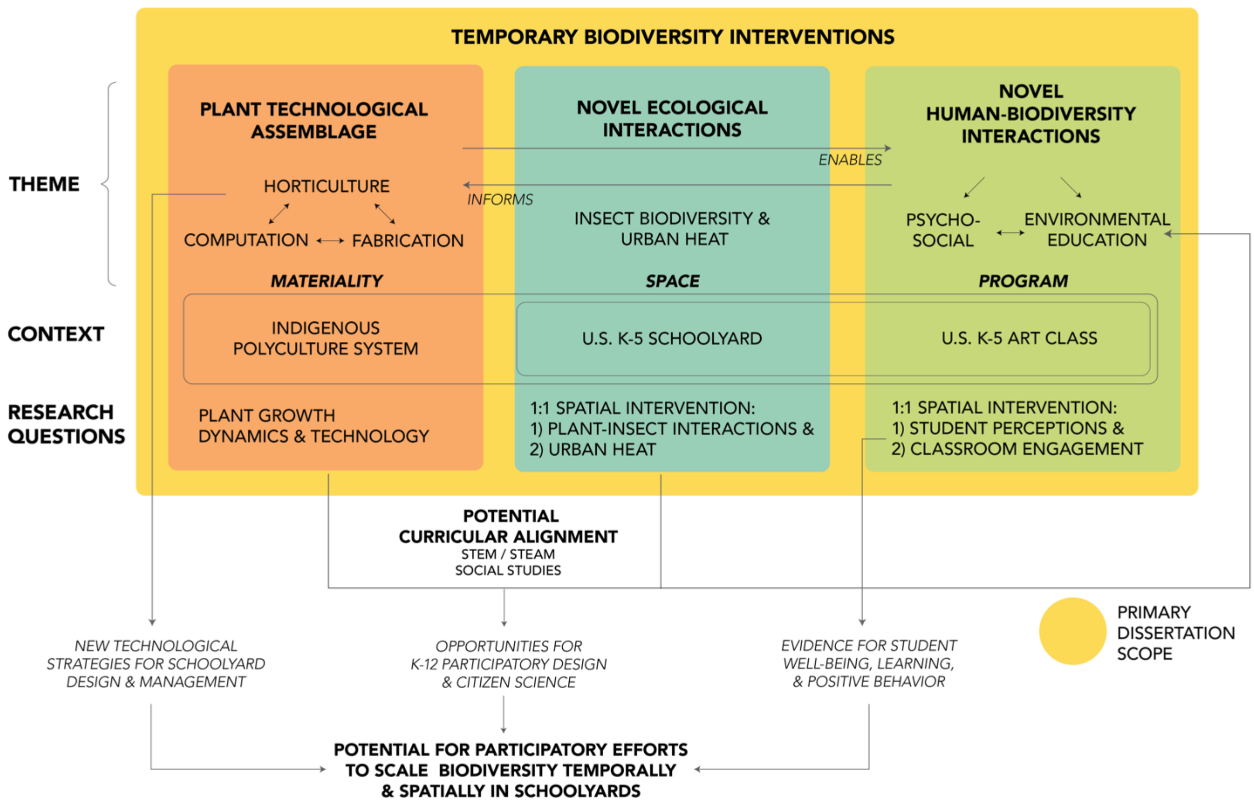


Figure 1: Interdisciplinary framework of dissertation

The decision to explore temporary biodiversity through an interdisciplinary, multi-domain framework emerged for three reasons. First, there has not been significant research on the concept of temporary biodiversity in any of these knowledge domains (Fig. 2). A literature review of Web of Science and Education Resources Information databases produced only three peer-reviewed publications and one book with relevance to the dissertation's themes and associated terms. A 1:1 scale installation would allow for simultaneous exploration of all three underexplored knowledge domains.

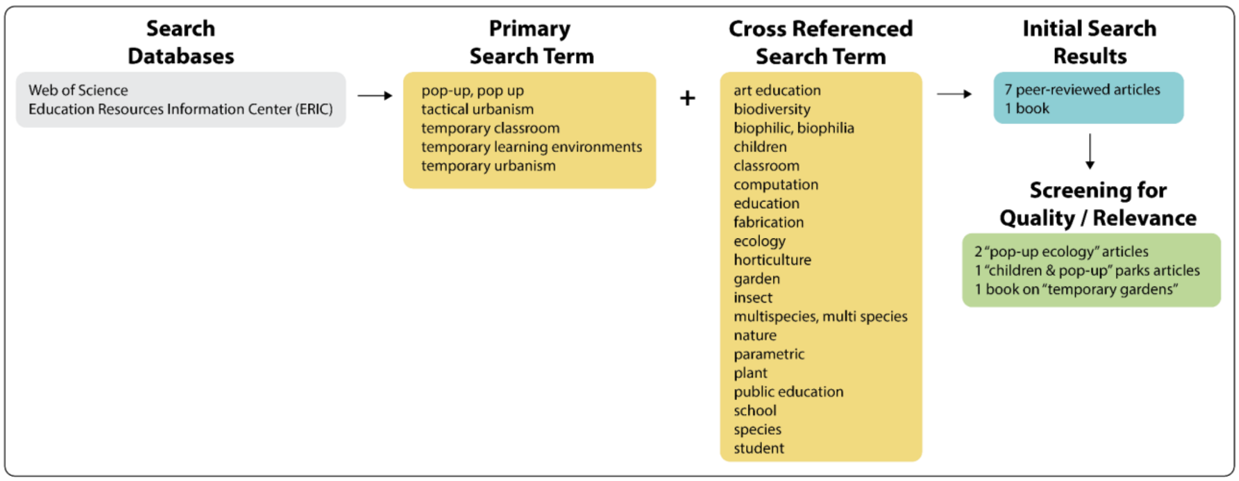


Figure 2: Initial literature review on key terms and themes of dissertation

Secondly, temporary biodiversity interventions could provide a unique testing ground for illuminating theoretical relationships between these knowledge domains. Investigation of the underlying technological assemblage required (i.e. horticulture, fabrication, etc.) could inform deployment and scaling of 1:1 interventions (spatially and temporally) with implications for ecology and human behavior research. Equally, ecology and human behavior research have many connections. Yet the multi-faceted relationships of 1) biodiversity in the built environment and 2) the human experience of biodiversity in the built environment are not clearly elucidated. From an ecology-centered perspective, theories of landscape ecology provide explanatory power for how biodiversity and ecological processes occur across heterogenetic spatio-temporal scales (Dramstad et al., 1996; Forman & Godron, 1991) but have not been as well researched in the typically fragmented habitats of urban landscapes (Lambert & Schell, 2023; Muderere et al., 2018). From a human-centered perspective, the experience of biodiversity is in the built environment is complex and touches on health and well-being (Davis et al., 2025; Lambert & Schell, 2023; Marselle et al., 2021), education (Navarro-perez & Tidball, 2012), and values/norms (Soga et al., 2023; Soga & Gaston, 2016). Simultaneously exploring 1) ecology and 2) human behavior through temporary biodiversity interventions could further develop their linkages, with technology-mediated design assemblages providing the means for creating and scaling such investigations.

Finally, from an applied perspective, positive transitions in the complex socio-ecological context of public education and its schoolyards requires interdisciplinary approaches that bridge silos. Temporary biodiversity interventions could serve as pilot "nature-based, outdoor learning environments" and potentially catalyze longer-term improvements to schoolyard design and associated educational programming. For example, STEM/STEAM based curriculum could align the technological and ecological aspects of schoolyard through participatory science and design methods, as has been proposed with green walls (McCullough, 2018). Equally, the design, horticulture, and fabrication of interventions could align with vocational and/or maker-space oriented educational offerings. Curriculum was not empirically researched or within the scope of this work but may provide a linkage between these three domains in the future and is discussed in the conclusion.

Design-Mediated Empirical Research

This dissertation's aim emerged four years ago with a design-based concept as its inceptor: the potential for designed, constructed, temporary biodiversity interventions to serve as both a tool for research and for participatory change. Over time, the central method that emerged was coined *Biophilic Tactical Urbanism* (BTU; Fig. 3). BTU method pulls extensively from the ethos and approaches of *tactical/temporary urbanism* (T/t urbanism) – the reimagination of public space through temporary, low-cost spatial interventions (Bishop & Williams, 2012; Lydon & Garcia, 2015; Stevens & Dovey, 2022). *Biophilic* draws from biophilic design – "creating good habitat for people as a biological organism in the modern built environment that advances people's health, fitness and wellbeing" (Kellert & Calabrese, 2015). Finally, the method privileges non-human centered perspectives on biodiversity, inspired by multispecies design concepts (Metcalfe, 2015; Roudavski, 2020). These three intersected design theories are discussed in Chapter 2. Design Intervention Literature Review.

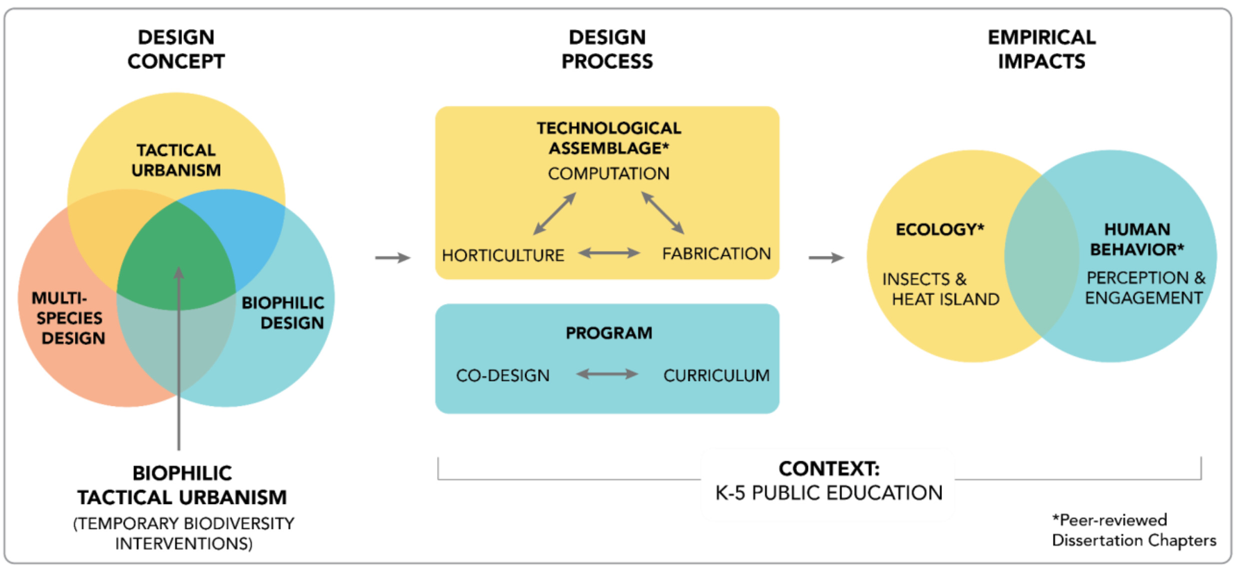


Figure 3: Conceptual logic model of dissertation

Biophilic design, multispecies design, and T/t urbanism were put in dialogue with each other at a 1:1 scale within the built environment through interventions featuring plant biodiversity armatures. These interdisciplinary investigations explored design and scientific aspects of BTU through increasing levels of complexity through scaffold research in Chapters 4-6 (Fig. 4), beginning with foundational horticulture/fabrication technology assemblage research on plant growth in architectural contexts (i.e. technology & BTU), continuing to the ecological impacts of BTU on insects & heat (i.e. ecology & BTU), and culminating in research on impacts of a BTU system on elementary students (i.e. human behavior & BTU).

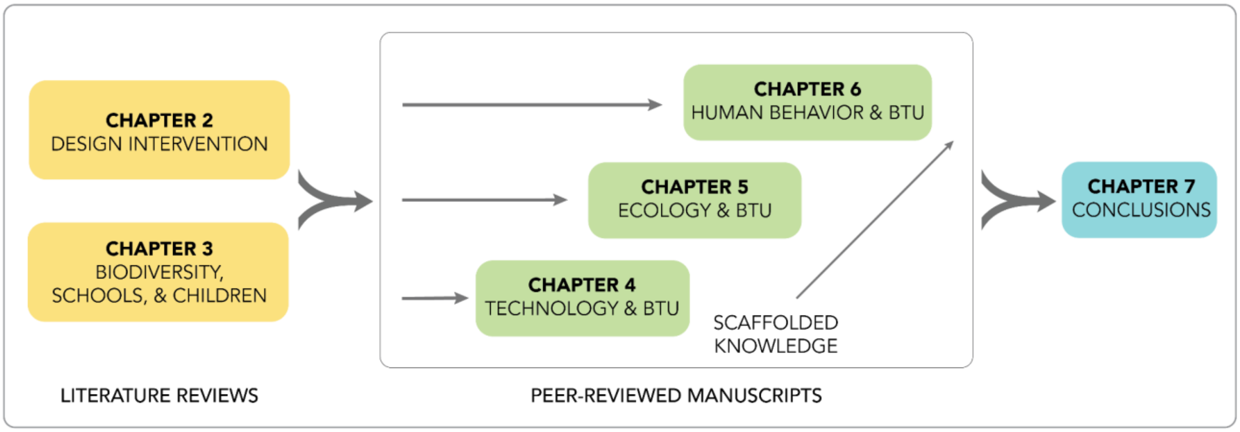


Figure 4: Structure of dissertation chapters and relevant themes/areas of empirical research

Public Schoolyards as Testing Grounds for Biophilic Tactical Urbanism

Most of the background and specific research questions for each knowledge domain (technology, ecology, and human behavior) are found within their relevant chapters. However, this work ultimately seeks to promote empirical strategies for the greening of public school outdoor learning environments and requires framing. The research was positioned in the spatial and programmatic context of these environments, in part because the myriad benefits of nature exposure and engagement on child learning and well-being writ large have been well documented (Bikomeye et al., 2021; Chawla, 2015; Kuo et al., 2022; Roe & Aspinall, 2011). At the same time, there remain unexplored empirical questions on the relationship between biodiversity specifically and children's well-being and environmental education, beyond the basic notion that "nature is good for kids" (Davis et al., 2025). Here biophilic tactical urbanism provides an experimental classroom condition for investigated underexplored biodiversity-children research questions.

From an applied perspective, the spaces of public education in the U.S. and beyond are often bereft of high-quality outdoor learning spaces enriched with biodiversity (Barnes & Barnes, Audrey, 2023; Kuo et al., 2021; Schulman & Peters, 2008) – an ideal applied testbed for biodiversity-oriented space-activation from an equity perspective. Public schools are formative public spaces for children and their broader communities. Most U.S. K-12 students attend public schools (82%; Fabina et al., 2021), for 13,000+ hours between kindergarten and 12th grade (DeSilver, 2023). Beyond the education communities they serve, public school yards are typically one of the largest municipal land holdings of local governments (25% of local government land holdings in the focal community of this dissertation; (*City of Harrisonburg, VA GIS*, 2011). Schoolyards often act as public parks after hours and natural resources for their communities. In other words, the multi-benefits of schoolyards extend beyond their education-focused missions (Fig. 5). Once again, temporary biodiversity intervention, framed as BTU, could help understand and promote public education infrastructure changes towards multi-benefits in these environments.

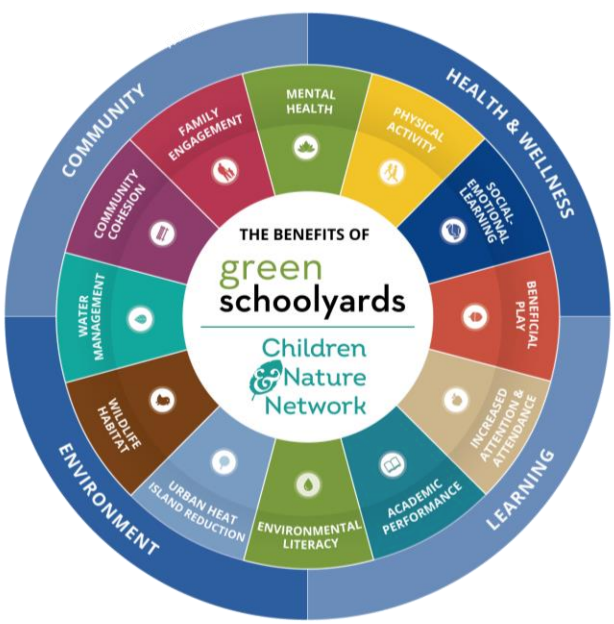


Figure 5: Multi-benefit framework for the benefits of green schoolyards (Children & Nature Network, 2022)

To explore these questions in a place-based frame, this dissertation engaged closely with a public school community. The research occurred in partnership with a public elementary school in response to a need for more outdoor learning environments. The partnership began in 2022 when $3 million in federal funds earmarked for permanent outdoor classrooms across the specific school district were reappropriated at a very late stage; final design drawings were already completed, and public media had shared these plans (Urenko, 2022). This unfortunate setback catalyzed a conversation among the author (a parent of children at the school), partner art teacher, principal and school district superintendent, and collective interest in a T/t urbanism intervention emerged. Though these participatory processes are not empirically investigated as part of this dissertation (Fig. 2), this important context set the path for the collaborative process that resulted in the BTU outdoor classroom and associated research study in Chapter 6 [Human Behavior].

Ultimately, this body of work is emergent and method centric. It aims to innovate new tools and approaches for enriching biodiversity within the built environment, specifically learning environments, through technological intervention, and then evaluating the socio-ecological impacts of the intervention. The dissertation can be thought of as a proof of concept–a multi-level case study for temporarily activating biodiversity in novel environments, especially those intended for learning.

1.3 Overview of Chapters

Chapter 2 [Literature Review 1]: Design Intervention frames the theoretical foundations of the BTU intervention employed in later chapters. The intersection of tactical/temporary urbanism (Lydon & Garcia, 2015), biophilic design (Kellert et al., 2011), and multispecies design (Weisser et al., 2023), are collectively explored for connections to biodiversity, and when possible, learning environments and technology. Biophilic tactical urbanism as a novel intersection of these three concepts is then proposed.

Chapter 3 [Literature Review 2]: Biodiversity, Schools, & Children provides a foundational interdisciplinary literature review on biodiversity and children and identifies knowledge gaps in theory and inequities in public school design. The chapter begins with a framing of the biodiversity crisis, focusing on cities and the built environment. The specific spatial, historic, and programmatic context of U.S. public education and their outdoor learning environments is then explored. This provides a linkage to the student experience of biodiversity at the individual and classroom scale, focusing on engagement and perception.

Chapter 4 [Technology]: Cultivating Computationally - Parametric Methods of Plant Growth Dynamics for Multispecies Design is positioned as a design research chapter exploring fundamental interactions of plant cultivation behavior with the built environment, with these design insights informing the horticulture/fabrication of the BTU system in later chapters. Drawing from landscape architecture, plant sciences, and horticulture, this chapter investigates plant growth as an entry point for developing a more integrated, computationally derived architecturally centered understanding of multispecies design (Grobman et al., 2023; Weisser et al., 2023) in the built environment. Plant growth and resulting morphology represents a quasi-algorithmic process driven in part by external stimuli like resource availability and disturbance regimes. To expand this knowledge base and position it in a computational design perspective, a series of plant training experiments using the indigenous polyculture system of the Three Sisters (Pleasant, 2006) were conducted, exploring plant behavior at the architectural interface. The Three Sisters was selected because it serves as a fast-growing multispecies system for modeling ecological and morphological complexity, while also providing a unique opportunity to engage with cultural history within the public education setting of Chapter 6 [Human Behavior]. Moreover, in addition to producing new knowledge at the nexus of plant growth and morphology, technology, and the built environment, the methods, tools, and horticultural expertise acquired in this chapter directly guided the development of Biophilic Tactical Urbanism in Chapters 5 [Ecology] and 6 [Human Behavior]. This chapter is reproduced with revisions from "Cultivating Computationally: Parametric Methods of Plant Growth Dynamics for Multispecies Design" published in *ACADIA*.

Chapter 5 [Ecology]: Biophilic Tactical Urbanism - Experiments between Temporary Architecture and Multispecies Design introduces the BTU system: a low-cost, mobile, modular planter system for rapid deployment of plant biodiversity into learning environments and beyond. The intervention was installed in the context of a public elementary school parking lot in the Mid-Atlantic U.S. This paper describes the results of BTU on surrounding ecological systems, including invertebrates like bees and butterflies as a metric of multispecies impact. Additionally, effects on urban heat were examined. Elements of landscape ecology (Forman & Godron, 1991) and multispecies design (Grobman et al., 2023) inform the aim and strategies of this chapter. Landscape ecology – a branch of ecology that explores the pattern and interaction between ecosystems, especially the effects of landscape spatial heterogeneity on these interactions – provides a theoretical foundation for how the temporary ecologies of BTU emerge at the micro-spatial scale. Three planting design conditions representing different degrees of biodiversity were tested. Results indicate that temporary ecology can have a significant effect on the ecology of public space even at small spatial and temporal scales. This chapter is reproduced with revisions from "Experiments in Temporary Architecture, Multispecies Design, &

Invertebrate Biodiversity" published in *Proceedings of Divergence in Architectural Research, 2024.*

Chapter 6 [Human Behavior]: Biophilic Tactical Urbanism in an Elementary Schoolyard explores the impacts of the BTU system on student classroom engagement and perceptions of nature in a public school context. Schoolyard greening has emerged as a potent strategy for improving child health, learning, and pro-environmental values (Stevenson et al., 2020). This chapter extends research into schoolyard greening through BTU, comparing a temporary, nature-based classroom to a conventional K-5 classroom. Student classroom engagement was measured via attention redirects, teacher ratings, and student instructional activity, with a prediction that the pop-up classroom would improve all measures of student engagement compared to a conventional indoor control classroom. These results found significantly improved student engagement in the outdoor pop-up biodiversity classroom. An additional exploratory line of research investigated student perceptions of nature in the pop-up biodiversity classroom through nature photography methods. Student photographs were analyzed for insight into their perceptions of biodiversity in the environment across three grade levels (1, 3, 5). This chapter demonstrates the potential for temporary greenspace manipulations to affect student classroom engagement and perceptions of biodiversity, while also demonstrating novel architectural and perceptual methods for understanding the impact of nature on students. The chapter is reproduced with revisions from "From Asphalt to Ecosystems: Classroom Engagement and Perceptions of Participatory Biophilic Tactical Urbanism in an Elementary Schoolyard" submitted to the journal *Environmental Education Research*.

Chapter 7: Conclusion - provides an interdisciplinary, integrated perspective on the socio-ecological investigations of BTU in Chapters 4-6 and raises ideas for future work. Throughout this dissertation the notion of BTU is positioned as an interdisciplinary proof of concept. How successful was it? What incipient research questions emerged from this body of work? How might BTU be scaled to achieve greater impact on children and ecology–spatially, temporally, and programmatically? The role of technology and stakeholder engagement are explored specifically, and potential research threads are framed.

Chapter 2 [Literature Review 1]: Design Intervention

Ephemeral gardens feature as essential elements of a 'temporary city' that seems 'eternally unfinished' -urbanity conceived as informal, evolving laboratory of ideas and strategies, tactics, and design processes that set places in motion both practically and intellectually (189)

(Sini, 2022)

2.1 Chapter Summary

As a designed-oriented dissertation that builds towards 1:1 biodiversity interventions, this chapter provides background research on the design movements that ground the eventual BTU intervention theoretically. Specifically, the intersection of tactical/temporary urbanism (aka T/t urbanism; (Lydon & Garcia, 2015), biophilic design (Kellert et al., 2011), and multispecies design (Weisser et al., 2023) are explored for connections to 1) biodiversity/ecology, and when possible, 2) learning environments, and 3) technology. The period of focus is the early 21st

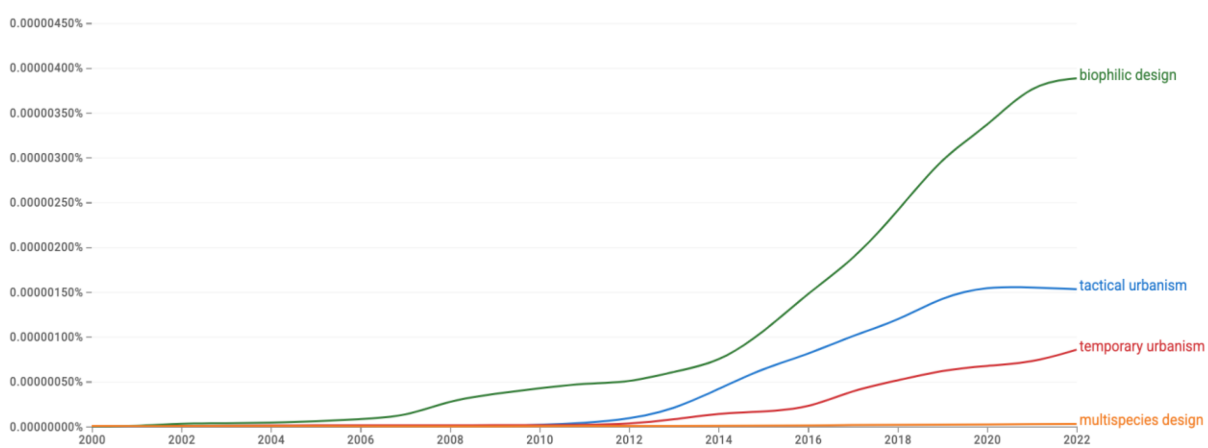


Figure 6: Ngram of relevant terms (biophilic design, multispecies design, tactical urbanism, and temporary urbanism) in published literature between 2000-2022

century to present, acknowledging that related concepts existed earlier. For example, efforts to activate public space through bottom-up DIY actions have occurred in the global north and global south for many years (Talen, 2015), but these actions were not necessarily described as T/t urbanism. Notably, the three modern concepts were independently developed in a short period between 2000-2015 (Fig. 6 and Fig. 7). From this review of T/t urbanism, biophilic design, and multispecies design, a cross comparison of these ideas and their integration into unified design concept – Biophilic tactical urbanism – is proposed (Fig. 14).

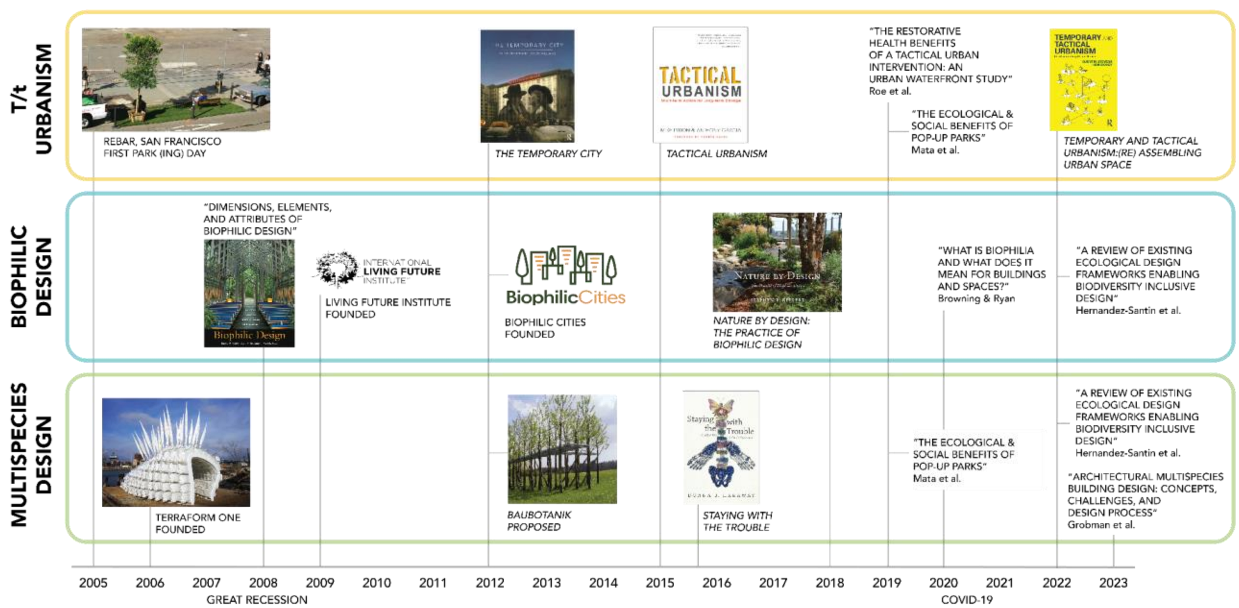


Figure 7: Relevant moments in the development of T/t urbanism, biophilic design, and multispecies design

2.2 Tactical/Temporary Urbanism

> *Time is not a given in the Anthropocene. Rather, it is designed, intentionally or accidentally. We cannot control the future, but we can participate in its choreography*
>
> (Milligan, 2022)

Tactical/temporary urbanism (T/t urbanism) is "an approach to neighborhood building and activation using short-term, low-cost, and scalable interventions and policies" (Lydon & Garcia, 2015). Among the many terms to describe this movement include insurgent urbanism (Hou 201), temporary urbanism (Bishop and Williams 2012), bottom-up urbanism (Arefi and Kickert 2019), and pop-up urbanism. Collectively these approaches are referred to here as T/t urbanism henceforth (Stevens and Dovey 2022). T/t urbanism has emerged as a ubiquitous global trend in urban design, with projects ranging from transportation (e.g., bike lanes), food production (e.g., guerilla gardens), and public space (e.g., parklets) (Fig. 8). These test-bed interventions often, but not always, serve as primers for more permanent changes to the built environment by catalyzing public engagement in the design of public space. For example, the conversion of New York City's Times Square from auto-centric to pedestrian-centric travel began with simple T/t urbanism (Lydon & Garcia, 2015).

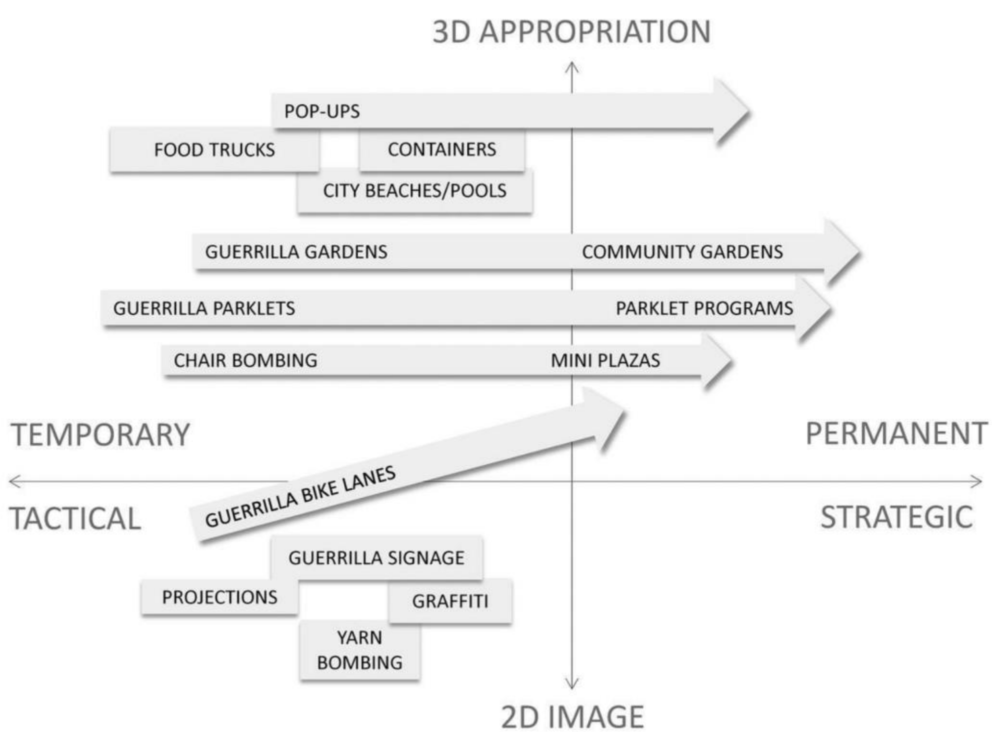


Figure 8: Tactical/temporary urbanism activity matrix (Stevens and Dovey 2022)

T/t urbanism as a modern design concept emerged in San Francisco in 2005 by *Rebar* (Fig. 10), who conceived the first Park(ing) day –a temporary park in a parking space (Coombs, 2012). From this beginning through the mid 2010s, interest in T/t urbanism grew rapidly. Park(ing) day expanded to global reach (*Park(Ing) Day*, 2025). At the same time new political forms of place activating approach emerged. For example, T/t urbanism can occur as bottom-up illicit activities catalyzed by concerned citizens by the failure of local government to enact change, such as the guerrilla street painting efforts in Los Angeles (Romo, 2022). Alternatively, authority-sanctioned efforts, such as the block redesign efforts of Barcelona (Schreiber, 2025), represent more top-down T/t urbanism. In other words, T/t urbanism works within a legality spectrum, meaning that sometimes the designed actions act against the norms to confront it in unsanctioned ways (guerrilla), and other times they are sanctioned by the city (central planning as primary drivers of change; Fig. 9).

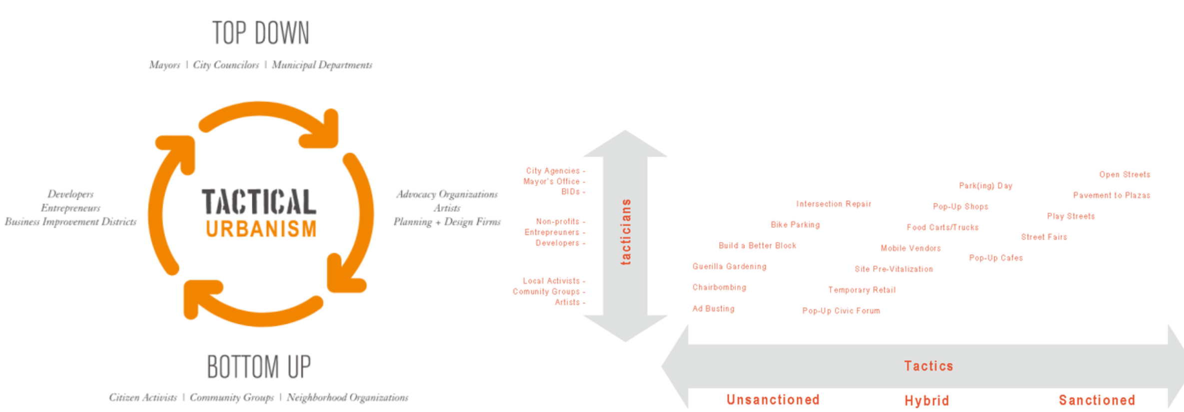


Figure 9: Top-down and bottom-up spectrum of tactical/temporary urbanism

More recently, Covid-19 dramatically changed how people use public space, and in turn ushered in a surge in temporary, pop-up strategies to maintain public health and safety (Laris & Lazo, 2021). Finally, community-driven design efforts such as Tiny WPA extend the ideas of T/t urbanism through workforce training and associated community outreach (B. Wilson, 2018).

Figure 10: Original tactical urbanism intervention by Rebar, San Francisco, 2005.

Not surprisingly, T/t urbanism interventions tend to focus on the needs and wants of humans rather than non-human actors, though the two are not mutually exclusive. However, its use as a tool for biodiversity empirical research in public space has been underexplored (Fig. 2). Notable exceptions that explicitly explore biodiversity include the American Society of Landscape Architecture's 2023 Park(ing) Day, which nationally focused on pollinator-based T/t urbanism (ASLA 2023) and a pop-up grassland research study in Melbourne, Australia (Mata et al. 2019) that explored impacts on insects and other arthropods (Fig.11). From a more critical design perspective focused on T/t urbanism through lens of temporary gardens, Sini proposes that "the temporary garden that has colonized cities since the new millennium is the manifestation of ephemeral urbanism, and an evolution of public art, which is becoming increasingly characterized by transiency, placeness, and ubiquity.” (Sini, 2022, p. 283). The historical roots draw parallels to “art, environmental art, earth art, and also performance art and conceptual art” whereby the activities are intended to provoke.

T/t urbanism in the context of public education schoolyards has not been empirically researched to the knowledge of the author, although no doubt many schools incorporate dynamic elements like moveable furniture as part of their outdoor learning environments. Regarding the intersection of technology and T/t urbanism, they are most explicitly linked through the processes of fabrication and material assemblage. The low cost, DIY approaches of T/t urbanism necessitate an accessible approach to technology, and numerous “how to” guides have been produced (Lydon & Garcia, 2015; Street Plans Collaborative, 2016, 2019).

Figure 11: Pop-up park ecological research project (Mata et al. 2019)

2.3 Biophilic Design

Biophilic design is defined as "creating good habitat for people as a biological organism in the modern built environment that advances people's health, fitness and wellbeing" (Kellert & Calabrese, 2015). It emerged from the Biophilia Hypothesis, which posits that humans have a natural tendency to connect with nature and other living things (Fromm, 1973; E. O. Wilson, 1986). From this initial hypothesis, biophilic design was developed into a range of design

2 Dimensions, 6 Elements, and 72 Attributes of Biophilic Design (Kellert, 2008b)					
I. Organic or Naturalistic				**II. Place-based or Vernacular**	
1. Environmental features	**2. Natural shapes and forms**	**3. Natural patterns and processes**	**4. Light and space**	**5. Place-based relationships**	**6. Evolved human-nature relationships**
• Color • Water^ • Air • Sunlight • Plants* • Animals* • Natural materials • Views and vistas • Façade greening* • Geology and landscape^ • Habitats and ecosystems* • Fire	• Botanical motifs • Tree and columnar supports • Animal (mainly vertebrate) motifs • Shells and spirals • Egg, oval, and tubular forms • Arches, vaults, domes • Shapes resisting straight lines and right angles • Simulation of natural features • Biomorphy • Geomorphology • Biomimicry	• Sensory variability • Information richness • Age, change, and the patina of time • Growth and efflorescence • Central focal point • Patterned wholes • Bounded spaces • Transitional spaces • Linked series and chains • Integration of parts to wholes • Complementary contrasts • Dynamic balance and tension • Fractals • Hierarchically organized ratios and scales	• Natural light • Filtered and diffused light • Light and shadow • Reflected light • Light pools • Warm light • Light as shape and form • Spaciousness • Spatial variability • Space as shape and form • Spatial harmony • Inside-outside spaces	• Geographic connection to place • Historic connection to place • Ecological connection to place* • Cultural connection to place • Indigenous materials • Landscape orientation • Landscape features that define building form • Landscape ecology* • Integration of culture and ecology* • Spirit of place • Avoiding placelessness	• Prospect and refuge • Order and complexity • Curiosity and enticement • Change and metamorphosis • Security and protection • Mastery and control • Affection and attachment • Attraction and beauty • Exploration and discovery • Information and cognition • Fear and awe • Reverence and spirituality

3 Experiences and 25 Attributes of Biophilic Design (Kellert, 2018)		
1. Direct Experience of Nature	**2. Indirect Experience of Nature**	**3. Experience of Space and Place**
• Light • Air • Water^ • Plants* • Animals* • Landscapes^ • Weather • Views • Fire	• Images • Materials • Texture • Color • Shapes and forms • Information richness • Change, age and the patina of time • Natural geometries • Simulated natural light and air • Biomimicry	• Prospect and refuge • Organized complexity • Mobility • Transitional spaces • Place • Integrating parts to create wholes

3 Categories and 15 Patterns of Biophilic Design (Browning and Ryan, 2020)		
1. Nature in the Space	**2. Natural Analogues**	**3. Nature of the Space**
• Visual Connection with Nature^ • Non-Visual Connection with Nature^ • Non-Rhythmic Sensory Stimuli • Thermal & Airflow Variability • Presence of Water^ • Dynamic & Diffuse Light • Connection with Natural Systems^	• Biomorphic Forms & Patterns • Material Connection with Nature • Complexity & Order	• Prospect • Refuge • Mystery • Risk/Peril • Awe

Figure 12: Three most cited biophilic design frameworks. * = attribute connects directly to biodiversity, ^ = attribute partially associated with biodiversity (source: (Zhong et al., 2022), modified by author)

frameworks, checklists, and associated guidance with a particular emphasis on application for architecture and the building scale. Collectively, these resources focus on incorporating nature, biomimicry, and related aspects of human behavior into the design of space (Zhong et al., 2022). Notably, there is no single, unified framework, and each interprets the concept of biophilic design in different ways. An overview of the three most cited frameworks is provided (Fig.12).

Kellert in his two frameworks for biophilic design (Kellert, 2008, 2018) incorporates elements of biodiversity through descriptive environmental features. For example, attributes such as "plants" and "animals" provide direct linkages to biodiversity, while place-based attributes such as "integration of culture and ecology" and "ecological connection to place" connect to biodiversity through ideas of culture and place attachment (Zhong et al., 2022). "The most effective biophilic landscapes, then, are generally composed of interconnected soils, waters, plants, animals, and geological forms revealed in a space that is ecologically coherent. These integrated and typically more resilient landscapes usually have high levels of biodiversity" (Kellert, 2018). However, Kellert does not provide further guidance on how biodiversity aligns with his biophilic design frameworks.

Browning and Ryan's framework focuses more on the functional role of design elements for human users and does not explicitly incorporate elements of biodiversity (Browning & Ryan, 2020). For example, "visual connection with nature" implies a non-human environment, but how biodiversity manifests in the framework is not clarified. Stepping back, none of the three biophilic design frameworks approach biodiversity and/or non-human relationality in an intentional, inclusive way (Hernandez-Santin et al., 2022). Biophilic design is thus best categorized as a human-centered approach focusing on the benefits we receive from nature-oriented built environments, with incidental benefits to biodiversity. For example, a building that featured monoculture non-native invasive plants that were incorporated in well-designed ways from a human perspective could be "biophilic" but might provide neutral or negative biodiversity benefits.

Biophilic design has several linkages to the design of quality learning environments. Foremost, biophilic design draws from theories of environmental and evolutionary psychology, where the benefits of well-designed buildings that incorporate elements such as natural light, greenery, and biomimetic patterns have been shown to improve health and wellbeing (Gillis & Gatersleben, 2015; Hung & Chang, 2021). These benefits extend to formal learning environments including university and K-12 settings (Fisher, 2024; Ghaziani et al., 2021; Peters & D'Penna, 2020) and research has shown improved student health and well-being (Leif & Loftness, 2024), as well as academic success (Determan, 2019).

The relationship between biophilic design and technology is less clear as it is not explicitly addressed in the three primary frameworks. Perhaps the clearest connection is through the material selections and assemblages of biophilic design (e.g. material connection with nature (Browning & Ryan, 2020)).

2.4 Multispecies Design

Multispecies design is "the practice of designing systems and artefacts that address the needs of humans as well as [non-human] species" (Metcalfe, 2015). In other words, multispecies design focuses on habitat creation for more biodiverse built environments. Among the three terms discussed in this chapter, multispecies design is the most recent and least developed. It emerged from post-humanist perspectives on non-human life including the *animal turn* from the humanities (Ritvo, 2007) and *reconciliation ecology* from the natural sciences (Francis &

Lorimer, 2011). Multispecies design is closely related to *More than human design* (Giaccardi & Redström, 2020), animal-aided design (Weisser & Hauck, 2017) and *living architecture* (Cogdell, 2019). More recently, *biodiversity inclusive design* (Hernandez-Santin et al., 2022), has been proposed as a similar non-human centric design framework.

Multispecies design is typically positioned as design strategies at either the building scale (Grobman et al., 2023) such as on-building greening, or speculative contexts where the intention is to spark discourse about ontological repositioning of humans and the non-human world (Edwards & Pettersen, 2023). Notably, notions of multispecies design have existed in the field of landscape architecture, arguably since its inception and long before the modern term was described. Historic and modern practices of planting design, plant cultivation, and biodiversity protection all speak to the spirit of multispecies design and are well rooted in the field (Girot, 2016; Mooney et al., 2019; Park et al., 2024; Raxworthy, 2019). In this sense, multispecies design as an emerging concept can be thought of as architecture and other design fields "catching up" to landscape architecture's engagement with biodiversity more broadly.

There has not been any peer-reviewed research on the relationship between multispecies design and learning environments to the knowledge of the author. As an emerging and often speculative concept that straddles between non-human life and the built environment, multispecies design privileges technology and technological innovation (Fig. 13).

Figure 13 (Clockwise): Examples of multispecies design - “Baubotanik Footbridge” by Ferdinand Ludwig; “Bee Conservancy” by Harrison Atelier; “Fab Tree Hab” by Terraform One; “Platform for Humans and Birds” by Studio Ossidiana.

2.5 Biophilic Tactical Urbanism

> *Temporary gardens are that experimental ground where designers can investigate and question ideas and practices that inform landscape, garden and urban desig*n (23)
>
> (Sini, 2022)

Based on this literature review, biophilic design, multispecies design, and T/t urbanism each have distinct relationships with 1) biodiversity, 2) learning environments, and 3) technology

(Table 1). Biophilic design is positioned from a human-centered perspective, has the most developed frameworks, and has seen a relatively greater acceptance as a term associated with human well-being and green building in the architecture and building industries. Multispecies design repositions “design with nature” to a more even ontological footing between humans and non-humans; however, has not been as developed in terms of a practical framework. T/t urbanism emphasizes the short-term intervention but does not typically incorporate a theoretical or practical integration with biodiversity.

	BIODIVERSITY	LEARNING ENVIRONMENTS	TECHNOLOGY
T/t URBANISM	X	X	LOW-COST, ACCESSIBLE FABRICATION & ASSEMBLAGE
BIOPHILIC DESIGN	EMPHASIZES HUMAN-CENTERED BENEFITS	INFORMS BEST PRACTICES	MATERIAL SELECTION & ASSEMBLAGE
MULTISPECIES DESIGN	EMPHASIZES NON-HUMAN HABITAT CREATION	X	SPECULATIVE & ON-STRUCTURE / BUILT ENVIRONMENT TECHNOLOGIES

Table 1: Relationship between 1) T/t urbanism, biophilic design, and multispecies design and 2) biodiversity, learning environments, and technology. X=unclear, underdeveloped relationship

Collectively, these three terms were synthesized in this dissertation to form the idea of Biophilic Tactical Urbanism (BTU; Fig. 14). This provided the conceptual underpinning for the design of a BTU intervention and research studies in Chapter 4 [Technology], Chapter 5 [Ecology], and Chapter 6 [Human Behavior]. A similar design precedent can be seen in MAS Studio’s Cut Join Play (Fig. 15), where a temporary installation design to catalyze change (T/t urbanism) incorporated parametrically generated planting design “cells” (technology) to emulate a natural environment (multispecies design/biodiversity) and that would be an appealing and engaging nature-inspired habitat for people (biophilic design/learning environment).

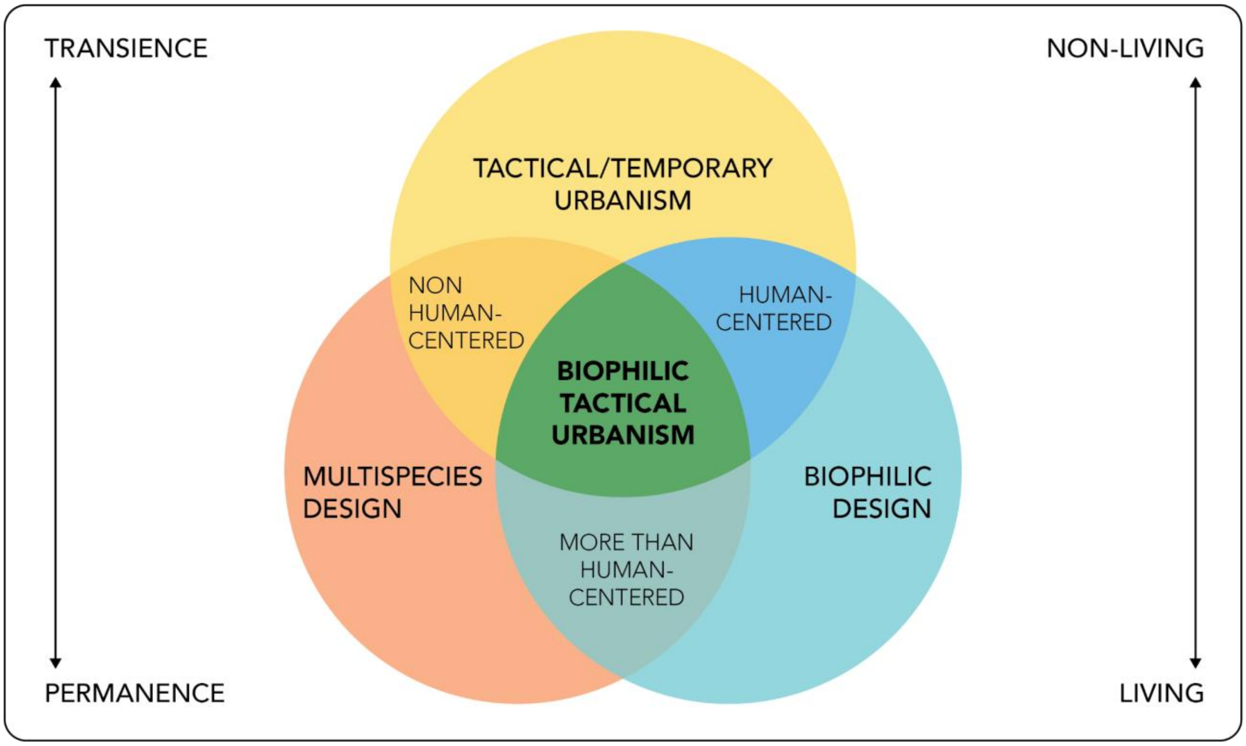


Figure 14: Conceptual relationship between Biophilic Design, Multispecies Design, and T/t Urbanism: Biophilic Tactical Urbanism

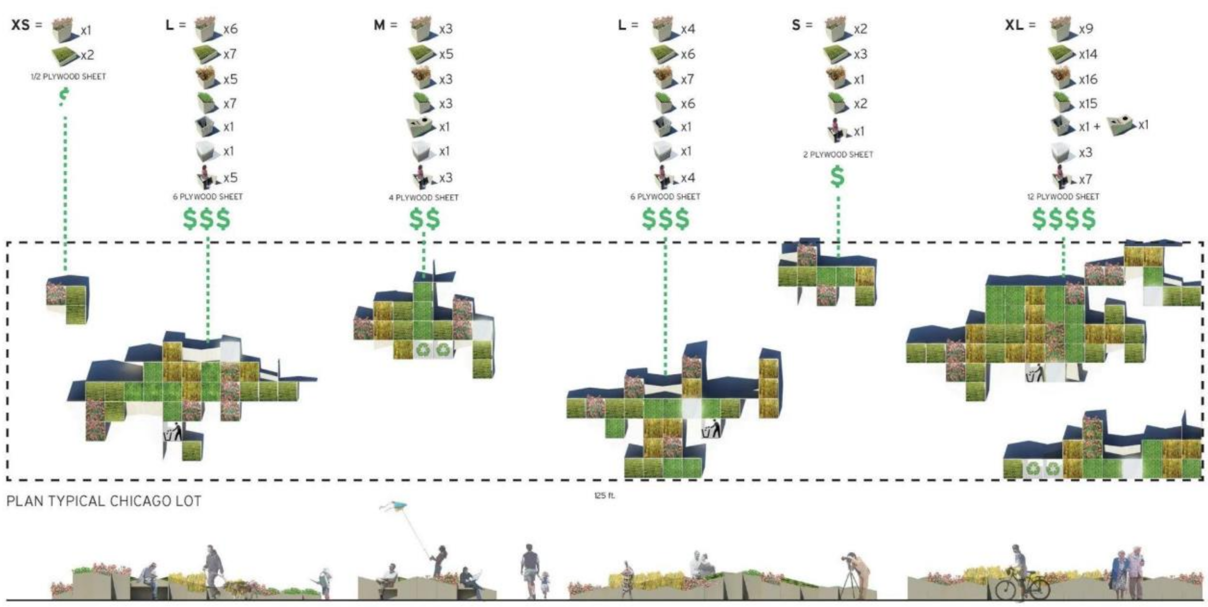


Figure 15: MAS Studio Cut Join Play 2010

Chapter 3 [Literature Review 2]: Biodiversity, Schools, Children, & Environmental Education

3.1 Chapter Summary

This chapter provides a foundational interdisciplinary literature review on biodiversity, children, public schools, and environmental education and identifies knowledge gaps, which collectively provide research context for biophilic tactical urbanism interventions in Chapters 5-6. The chapter begins with a framing of the biodiversity crisis, focusing on cities and the built environment. The specific spatial and programmatic context of U.S. public education outdoor learning environments is then explored, particularly formal education settings. This provides a linkage to the student experience of biodiversity at the individual and classroom scale, focusing on engagement and perception.

3.2 Biodiversity & The Built Environment

Biodiversity—a “simple word to describe the complex sum of all life on earth” (Bowers, 2024) and an underpinning for ecosystem services and human well-being (Haines-Young & Potschin, 2010)—is in crisis at a planetary scale. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), “around 1 million animal and plant species are now threatened with extinction, many within decades, more than ever before in human history” (IPBES, 2019). This has been described as the 6th mass extinction event in geologic history, driven by mostly human activity since the industrial revolution (Ceballos et al., 2020).

The built environment of cities, with its growing ecological footprint, has a unique role in this crisis. Globally, it is estimated that the built environment land cover will increase by “4.5

times by the year 2100 under middle of the road estimates” (Gao & O’Neill, 2020). Concurrently with these ecological and land-use trends, the world population is increasingly urban, with more than 55% of people living in urban areas and is expected to increase to 68% by 2050 (United Nations, 2018). Yet the ecologies of built environments and the associated human interactions have been historically understudied compared to rural and “wild” places (Gaston, 2010).

More recently, there has emerged a shift toward recognizing that urban environments are critical for addressing biodiversity challenges. Rather than being ecological wastelands, ecologists (Lambert & Schell, 2023; Spotswood et al., 2021), designers (Park et al., 2024), and planners (Tabb, 2020), increasingly cities as a “frontline” in biodiversity conservation and critical spaces to engage the public in these issues. For example, building from the concept of the Nature Pyramid (Beatley, 2012), the biodiversity we experience in our everyday lives, which is now typically urban, forms the foundation of our biodiversity “diet”, which in turn may influence cultural norms and values about non-human life. Equally, an “extinction of experience” (Soga & Gaston, 2016), whereby subsequent generations have a lowered baseline for nature could emerge, potentially producing a reinforcing feedback loop (Soga et al., 2023), including in children (Soga et al., 2020).

The dissertation specifically explored biodiversity in the built environment context of U.S. public school infrastructure. This decision emerged for several layered reasons. First, public schools are often one of the largest land holdings of local municipalities; they represent one of the most actionable local government levers for affecting biodiversity at larger scales. For example, school real estate accounts for 24% of municipal land holdings in Harrisonburg, VA, the city and school district where the human subjects research place occurred (*City of Harrisonburg, VA GIS*, 2011). At the same time, the outdoor environments of public schools including schoolyards, paved areas, and play spaces are often devoid of biodiversity and other types of ecological complexity (Barnes & Barnes, Audrey, 2023; Schulman & Peters, 2008), presenting an opportunity for intervention. The programmatic considerations and history of U.S. school infrastructure is explored more deeply in the following section: 3.3 History and Trends of U.S. Schoolyards.

Finally, from a student perspective, schools play an outsized role as a mediator between childhood and biodiversity. The average U.S. child spends approximately 13,000 hours in a public school setting between kindergarten and 12th grade (DeSilver, 2023) – a substantial portion of childhood. Through formal education, schools provide opportunities to promote pro-environmental values around biodiversity through environmental education (Lindemann-Matthies, 2002), as well as serving as testing grounds to elucidate potential impacts of biodiversity on student development, which are explored in 3.5 Engagement & Perception of Biodiversity in Children.

3.3 Environmental Education in the U.S.

The environmental education focus of this dissertation is bracketed by formal modes of education in the U.S. As background for the history of contemporary environmental education, it can be traced back to the nature study movement of the 19th century, including works such as *Nature study for the common schools* (Jackman, 1894), which emphasized firsthand observation and experience with natural phenomena. These works laid the groundwork for what would later align with constructivist educational theories. The associated pedagogical approaches, championed by educators like John Dewey (Dewey, 1923, 1938) and later informed by Piaget's cognitive constructivism (Piaget & Inhelder, 1966), posits that learners actively construct knowledge through interaction with their environment rather than passively receiving information. Building on these theoretical ideas, experiential learning became a hallmark of environmental and outdoor-based education in the mid 20th century (Quay & Seaman, 2013).

The evolution of environmental education gained significant momentum in the 1970s with the establishment of the United Nations Environmental Programme and the Belgrade Charter in 1975, which defined environmental education as a process enabling individuals to explore environmental issues, engage in problem solving, and take action (Eulefeld, 1979). Formal environmental education, typically situated within structured educational institutions with standardized curricula and assessment methods, evolved with the integration of environmental topics into traditional science education in the 1960s and 1970s.

These formal environmental education efforts contrasts to other constructivist ideas from informal of modes education such as adventure playgrounds. These originated in Denmark with landscape architect Sørensen's "junk playgrounds" in the 1940s (Brown & Hughes, 2018)—and emerged as physical manifestations of constructivist principles in environmental education, providing spaces where children could manipulate their surroundings, assess risks, and develop environmental stewardship through self-directed play and exploration. Though not directly related to the scope of this dissertation, which focuses on formal education, these informal ideas influenced how self-directed, experiential learning could be incorporated into the former settings, including the BTU intervention and future research potentials.

3.4 The Ecological Context of U.S. Schoolyards

> *"Schoolyards are mnemonic spaces that reflect previous as well as contemporary beliefs regarding education, childhood, and even nature."*
>
> Susan Herrigton, *Reflections on the North American Schoolyard*
> (Herrington, 2004)

The contextual focus of BTU for this dissertation was children's learning environments, specifically U.S. K-5 schoolyards and campuses, and associated formal education. The following section provides an overview of these spaces, historically, spatially, and programmatically, focusing on ecological needs and inadequacies where BTU interventions could effectively engage. The geographic focus was Virginia and the Southeast U.S. – when relevant data is available. Urbanizing, suburban, peri-urban contexts are also prioritized; highly urbanized settings (e.g. dense metropolitan areas such as New York City) represent unique typologies of schoolyards that are out of scope.

The term "schoolyard" here refers to open space, often equipped with playground equipment, sports courts, pavement, and grassy areas. Importantly, schoolyards exist in close tandem with the design of school buildings. Their collective form and programming emerge through trends in public education, architecture, and broader social priorities. Temporally, this work focuses on post-World War II through the 1970s, a period of rapid growth and suburbanization, which significantly influenced the design of schools and their environs. "The "Baby Boom" produced 76 million American babies between 1946 and 1964, which meant that school boards across the country were forced to meet the challenge of increased enrollment. Educators built as rapidly and as cheaply as possible" (Gyure, 2016). This International Style era of school building still dominates the types of public education buildings in use today. For example, in Virginia more than 50% of school buildings are 50 years old (Virginia DOE, 2021) and many represent the international style. This building style shared some characteristics with earlier, ornate typologies from the 1920-1950s such as building wings that provide ample light in all rooms and providing separation between classroom and noisier elements of the building such as gymnasiums, cafeterias, and music rooms. At the same time, international style buildings differed in that s were rarely more than two stories–a response to new fire codes (Gyure, 2016). The need for short story, large schools that could accommodate growth of populations outside urban cores resulted in the siting of buildings in large campus lots in suburban and peri-urban areas with larger grassy lawns, rather than urban cores (Fig. 16).

Figure 16: Postcards of Virginia schools and landscapes; Pre-WWII architectural and landscape styles above, Post-WWII International styles below

In this era, schoolyards became larger and more formalized, often featuring multiple sports fields, playground equipment, and recreational courts (Herrington, 2004). The rise of standardized testing and an increased focus on academic achievement relegated outdoor spaces to secondary status, focusing primarily on play and recreation during recess. This stood in contrast to earlier nature-based learning movements at the turn of the 20th century where elements like school gardening were incorporated into school pedagogy and site management, largely inspired by the work of Friedrich Fröbel on kindergartens (Froebel, 1886). The grass and pavement schoolyards that emerged in the mid-20th century still dominate the U.S. today including in the study region of this dissertation (Barnes & Barnes, Audrey, 2023; Schulman & Peters, 2008; Fig. 17). These trends exist for many reasons: resource constraints (mowing is a relatively inexpensive form of management), a strong landscape aesthetic for manicured lawns (Jenkins, 2015), a desire for sights lines for observing students, and cultural inertia. For example, teachers today may have negative attitudes about the benefits or ease of outdoor learning (Bilton, 2020), de-prioritizing nature-oriented landscape management by administrators.

Figure 17: Panoramic photography survey of 4 public elementary schoolyards and outdoor spaces

In the early 21st century a recognition emerged that children were spending less time outdoors in nature, with terms like nature-deficit disorder coming into the national lexicon (Louv, 2008a). Schools were considered critical for ameliorating this trend and a range of associated organizations and initiatives were started including the Natural Learning Initiative at NC State University (founded 2001), The Children & Nature Network (founded 2006), and Green Schoolyards of America in (founded 2013), along with countless local and state-wide greening schoolyard initiatives. In many ways, these initiatives draw from the historic ideas of Fröbel, more modern European ideas including forest schools which began to emerge a few decades earlier (Dean, 2019), and the growing body of research on the benefits of nature exposure on children's well-being and development (Chawla, 2015; Kuo et al., 2022; Roe & Aspinall, 2011). The range of potential benefits of schoolyard greening are increasingly seen through a broader community lens that extends beyond the property line and the hours of education (Fig. 5). Despite this, many U.S. public schools are devoid of significant ecological complexity and associated nature-based learning is not emphasized in curricula (Stevenson et al., 2020).

3.5 Engagement & Perception of Biodiversity in Children

Biodiversity interacts with human well-being and development in complex ways (Marselle et al., 2021; Robinson et al., 2024), including in children (Davis et al., 2025). This dissertation builds towards Chapter 6 [Human Behavior], which explores the effects of temporary biodiversity interventions on child experience in public schoolyards. However, there has not been any previous research on the effect of temporary biodiversity on human behavior to the knowledge of the author (Fig. 2), so the associated literature review focuses on biodiversity in a traditional, more permanent sense. Equally important, a large and growing body of research has explored the benefits of nature exposure on children in educational settings (Chawla, 2015; Kuo et al., 2022; Mann et al., 2022; Roberts et al., 2019). "Nature" often represents a larger, more abstract concept than the variety and abundance of species in a particular area (i.e. biodiversity). Yet the delineation between "nature" and "biodiversity" is not always clear. For example, exposure to greenspace (which includes biodiversity) has been shown to improve student performance (Kuo et al., 2021), attention, and lower stress (Li & Sullivan, 2016). How biodiversity might mediate these sorts of benefits is an unanswered question. Temporary interventions could provide a potential research tool for elucidating the specific role of biodiversity.

The impact of temporary biodiversity interventions were explored in Chapter 6 [Human Behavior] in the context of student classroom engagement and perceptions of biodiversity. These areas of research emerged in part through the co-design process with the partner schoolteacher, and in part because these represented theoretical spaces where the BTU method could provide new insights. First, student classroom engagement is defined as a "student's ability to pay attention and stay on task in class" (Miller et al., 2021). Lack of student engagement is considered one of the biggest challenges that teachers face in the classroom (Parsons & Taylor, 2011). It is affected by a range of factors including (Dotterer & Lowe, 2011):

1. Learning content
2. Learning strategies
3. Student choice and voice
4. Teacher-student relationship
5. Student factors

From a spatial perspective, outdoor, nature-based learning environments can support all of these factors, resulting in greater classroom engagement compared to conventional indoor classroom settings. For example, learning in an outdoor environment provides opportunities for different learning content (1), learning strategies (2), and for student choice and voice (3), which can support greater engagement (Harris, 2024; Kuo et al., 2018). Equally, teacher-student relationships (4) are also supported in outdoor, nature-based learning environments (Guardino et al., 2019). Student factors (5) like mental health are more restored in outdoor, nature-based learning environments (Roe & Aspinall, 2011).

What are the impacts of biodiversity (e.g. plant richness) in outdoor learning environments on student engagement? This question has not been empirically investigated to the knowledge of the author. However, research suggests that perceptions of biodiversity may be a key driver for a range of biodiversity-child interactions including engagement. Perception of biodiversity is a complex construct that involves both sensory information and subjective experience (Farris et al., 2024). People often perceive biodiversity poorly compared with the actual biodiversity present, including plants (Breitschopf & Bråthen, 2023), insects (J. S. Wilson et al., 2016), and in gardens with birds and pollinators (Shwartz et al., 2014). Moreover, a growing body of research suggests that the perceived level of biodiversity (compared to actual biodiversity) may be a stronger predictor of well-being (Dallimer et al., 2012; Gonçalves et al., 2021; Nghiem et al., 2021; Rozario et al., 2024; Schebella et al., 2019) and connectedness to nature (Southon et al., 2018). In other words, perceived biodiversity is a practical indicator for how people think about and experience biodiversity, with implications for psychology, environmental education, and classroom engagement. Just as perception represents a complex idea, biodiversity is, by definition, difficult to capture as it represents the abundant variety and distribution of life. Children may perceive different types of biodiversity very differently based on their life experiences and the specific context of exposure to biodiversity. Moreover, perception of biodiversity is not fixed and can shift through environmental education programs designed to improve student ecoliteracy about biodiversity (Lindemann-Matthies, 2002).

Chapter 4 [Technology]: Cultivating Computationally - Parametric Methods of Plant Growth Dynamics for Multispecies Design

4.1 Chapter Integration

This chapter is positioned as a technology research chapter exploring fundamental interactions between plant cultivation (mobile, container-grown plants) and the built environment, with these design insights informing the horticulture/fabrication of the BTU system in later chapters. It is reproduced with minor revisions from "Cultivating Computationally: Parametric Methods of Plant Growth Dynamics for Multispecies Design" published in *ACADIA*.

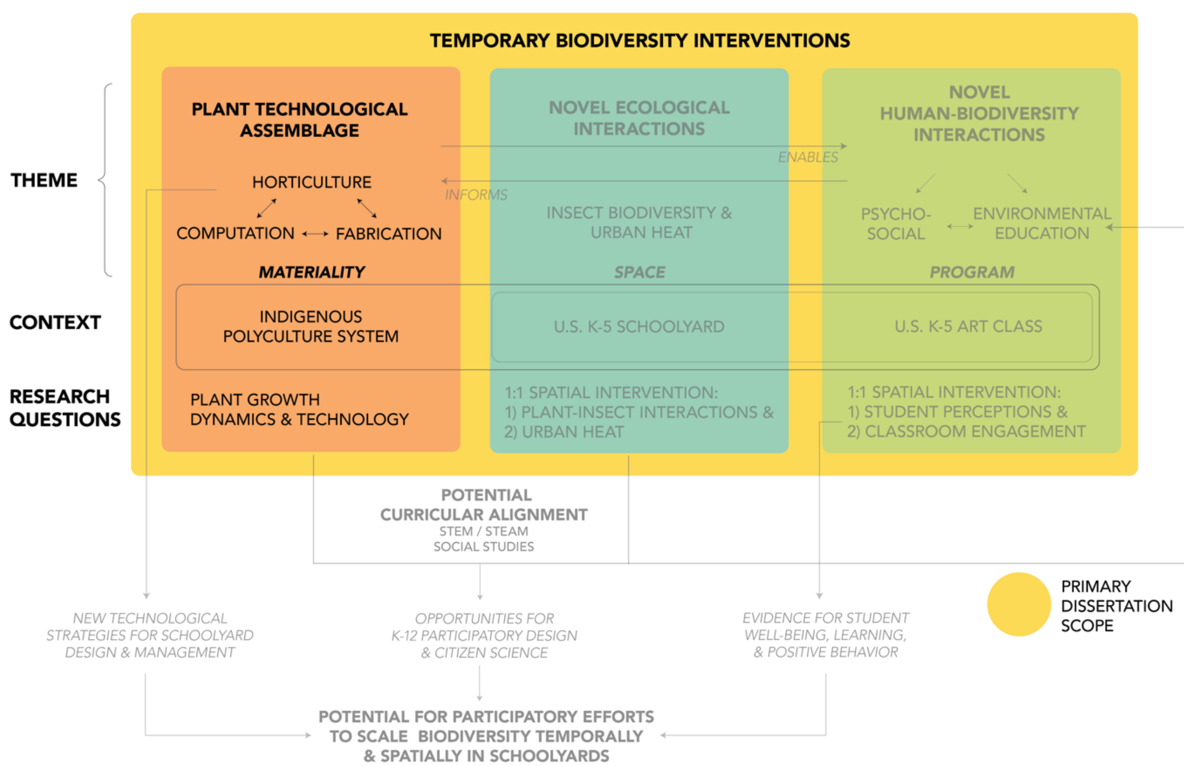


Figure 18: Interdisciplinary framework of dissertation – Plant Technological Assemblage

To expand the notion of "nature on wheels" and position it in a computational design perspective, a series of plant training experiments using the indigenous polyculture system of the

Three Sisters (Pleasant, 2006) were conducted, exploring plant behavior at the architectural interface. These focused on the above ground behavior plants because it represents the part of vegetation that humans readily engage with. The Three Sisters was selected because it serves as a fast growing multispecies system for modeling ecological and morphological complexity, while also providing a unique opportunity to engage with indigenous cultural history within the public education setting of Chapter 6 [Human Behavior]. Moreover, in addition to producing new knowledge at the nexus of plant growth and morphology/technology/built environment, the methods and horticultural expertise acquired in this chapter directly guided the development of the BTU intervention deployed in Chapter 5 [Ecology] and Chapter 6 [Human Behavior].

4.2 Abstract

This paper explores plant growth dynamics in the context of architecture through novel physical-digital modeling methods. Incorporating living organisms like plants into modern architecture could theoretically provide myriad benefits to the built environment of humans and beyond. Terms like multispecies design represent this emerging concept. Drawing from the plant sciences, horticulture, and landscape architecture, which all explicitly engage with plant dynamics, researchers investigated plant growth as an entry point for developing a more integrated, computationally derived architectural understanding of plant-centered multispecies design in the built environment. Plant growth, morphology, and training were specifically explored.

Growth and resulting morphology represent a quasi-algorithmic process driven in part by external stimuli like resource availability and disturbance regimes. Human intervention like pruning and bending can dramatically affect plant growth via emulation of these natural

processes (i.e. plant training). To expand this knowledge base and position it in a computational design perspective, a series of plant training experiments with model species were conducted and compared to predictions. The novel methods explored provide insight into plant behavior and performance under architecturally inspired spatial conditions and a foundation for future research.

4.3 Introduction

“Multispecies design” has emerged as an architectural term representing the intentional incorporation of plants, animals, and other organism’s needs in the design of the built environment (Grobman et al., 2023; Weisser et al., 2023). Increasingly, multispecies design strategies such as green roofs and walls have proliferated owing to the human and non-human benefits including improved building thermal performance, wildlife habitat, pollination services, noise reduction, aesthetic considerations, and beyond (Radić et al., 2019; Shafique et al., 2018). Plants are central to most multispecies design strategies as they provide countless ecosystem services and are the foundation of terrestrial food webs globally. In theory, design computation tools could uniquely support a predictive understanding of plant behavior in architecture with implications for design and performance. To further this emergent knowledge base, this paper explores novel methodological development focusing on the behavior and morphology of plants at the organismal scale and their response to architecturally-abstracted contexts. It considers the above ground growth and subsequent morphology of plants as a quasi-algorithmic process that could align with computational design approaches. Put as a question, how might plant cultivation be modeled computationally as a tool for multispecies design?

Design Implications

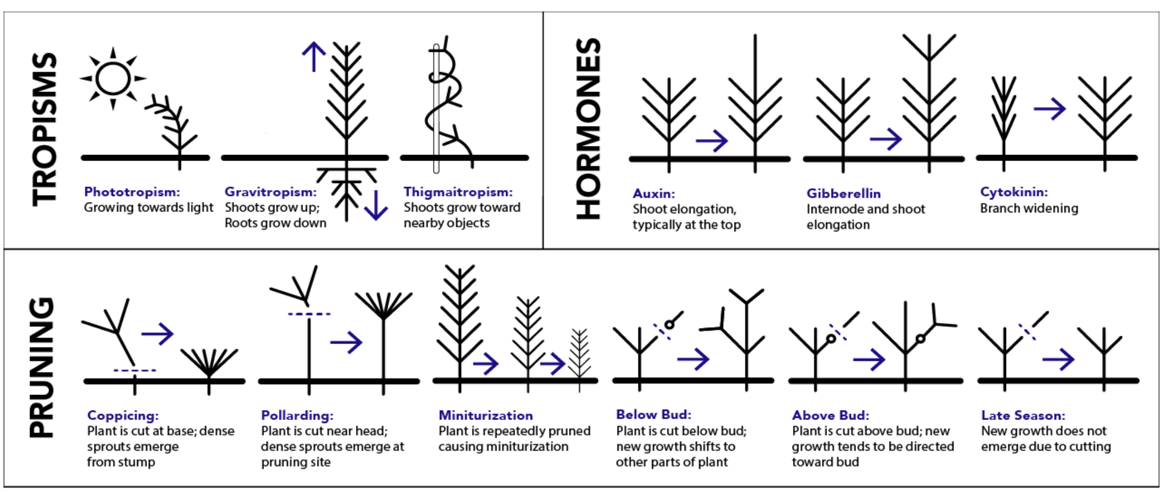
There are numerous implications for a more computational understanding of plant cultivation in multispecies design. At a simple, pragmatic level, computational cultivation of plants could support novel designs for green walls, green façades, green roofs and other eco-architectural systems that better match the morphological potential and performance of vegetation. Architectural precedents such as Bosco Verticale, Gardens by the Bay, and MFO Park, where plant dynamics are explicitly integrated into the design and maintenance regimes represent marquee examples of this potential future (Fig.18).

Figure 19: Multispecies architectural precedents: Bosco Verticale & MFO Park

For each, the close integration of living organisms with the building envelope provides a unique testbed for the aesthetics and performance potential of multispecies design. Ecolope (a blending of the terms ecology and building envelope) has been proposed as a data-driven, computational approach to modeling building-scale multi-species design (Weisser et al., 2023). At a more complex level, computationally informed systems could respond and manipulate plant growth and plant diversity to achieve specific design objectives, such as green walls that physically adjust to solar paths, akin to solar photovoltaic tracking systems. Finally, at its most aspirational, computational tools could extend designing with plants from a purely utilitarian perspective and provide a vehicle for a deeper programmatic engagement with plant ontology and intelligence. These provocative notions draw from plant science research which have explored agency in plant growth (Calvo et al., 2020), as well as philosophical critiques of plant utilitarianism drawing from theories of posthumanism (Hall, 2011).

Plants as Models

As primarily stationary organisms, plants have developed a suite of unique behaviors to grow towards resources, avoid disturbance and predation, and reproduce. From a biology frame, plants respond to external stimuli such as light and gravity through responsive growth behaviors, otherwise known as tropisms. The emergent form of plants results from this responsive, pattern-generating, problem-solving behavior. Humans have long taken advantage of these responses for cultivation purposes through practices like the training and pruning of plants, from the scale of the bonsai plant to the orchard. Morphological responses can be heuristically approximated (Fig. 19 & 20) though their form ultimately emerges through a responsive, semi-chaotic interaction between growth, resource availability, genetics, and human interaction.



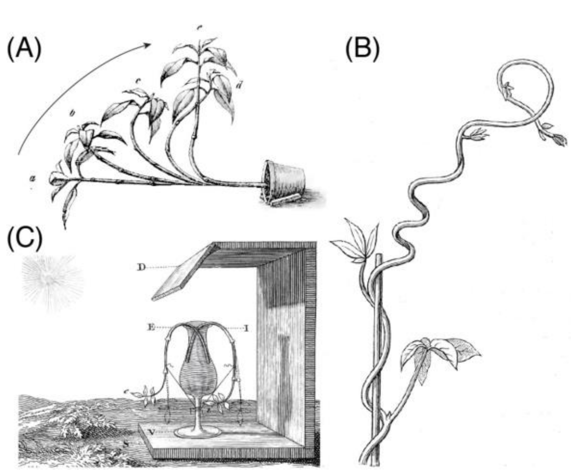


Figure 20: Parametric abstraction of common plant morphological response

Figure 21: Classic experiments on tropic responses by 18th century scientist Duhamel du Monceau

This interaction of humans and plants can be thought of as a type of dialogue, if an unhurried one by human timescales. Each act of plant manipulation represents a line of dialogue setting the stage for a series of future morphological possibilities. Physical, horticultural investigations of plant growth dynamics – plant training – were tested under a series of experimental conditions using model plant species. These conditions emerged from simple conceptual design objectives (e.g. growth on a pitched roof to explore the effect of slope). Conditions included slope, deflection, angled rotation, and agency. Collectively these conditions approximated architectural contexts where plants must meet performance objectives and spatial constraints such as green façades. Growth rates and dynamics over time were compared to modeled predictions through computational image analysis. From this research, the computational behavior of specific model species grown was explored, while at the same time, broader insight into digital-physical architectural methods and tools for multispecies design were elucidated.

4.4 State of the Art

Analog Knowledge

The foundational knowledge base for computational cultivation is broad, spanning a range of disciplines that include both physical and digital lines of development. From a physical frame, the cultivated behavior of plants has historically been the purview of gardeners, horticulturalists, arborists, and landscape architects, acquired through intimate engagement with plants over time, including practices in plant training (Girot, 2016). European traditions of espalier, pollarding, coppicing, etc. represent techniques for shaping woody plants such as trees and shrubs through pruning and branch training (Fig. 21). In Asia, the practice of bonsai represents a pinnacle of human-plant engagement; an intricate plant training relationship forms that can last multiple human generations. Another notable example is the tradition of growing Lucky Bamboo (*Dracaena braun*i) into unique, spiraling forms by repeatedly repositioning the plant: a response of gravitropism and phototropism.

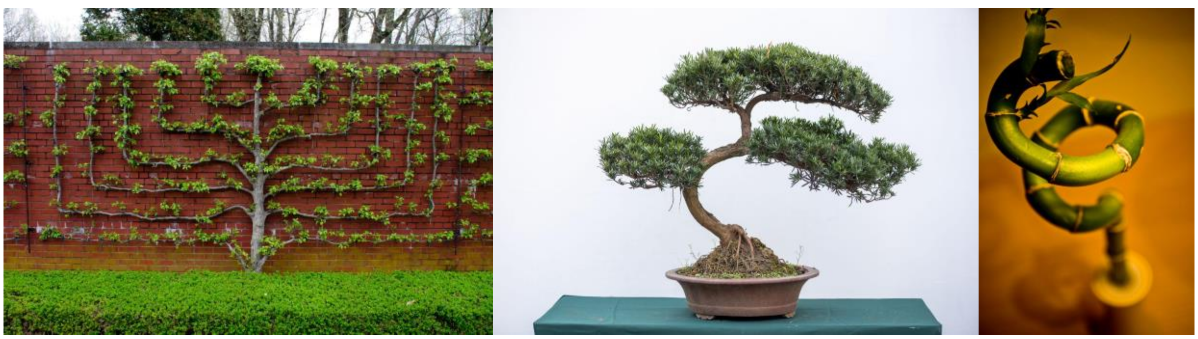


Figure 22: Horticultural plant training tradition: espalier, bonsai, lucky bamboo

Scientists have long explored the underlying mechanisms behind tropisms. Charles Darwin produced an entire book on the topic: *The Power of Movement in Plants* (Darwin, 1897). The biological and physical processes that drive tropism – and plant form – are driven by chemical signals within the plant vascular system (Friml, 2003). These chemical cues signal plants to respond to different environmental conditions such as light and gravity by adapting their position and growth. These changes are possible in undifferentiated meristem tissue, found in root tips, end shoots and lateral buds, and anywhere else new growth can occur (Ludwig & Schönle, 2023).

Tropisms can be described by their origin and sign (Moulton et al., 2020). Origin includes light, water, gravity, temperature, chemicals, touch, and magnetic fields. Sign explains the directional response of plants, either positive (towards the origin) or negative (away from the origin). Tropisms such as gravitropism, phototropism, and thigmotropism provide a foundational starting point for understanding and engaging plant behavior computationally as they are algorithmic in quality and have been mathematically modeled in the plant sciences. That being stated, the sheer diversity of plant species, their growth habits, and underlying genetics are important to consider in a discussion of tropisms and computational cultivation. For example, with pruning (which can drive tropic responses), many deciduous trees are adapted to heavy pruning. At the same time pruning of conifer tree species may not produce future growth because they lack latent (hidden) buds. This means that a more nuanced, species, taxa, or growth-form specific understanding of plant growth dynamics will be required for application to the field of architecture.

Digital Approaches

From a digital representation and modeling of plant morphology frame, procedural models including Lindenmeyer's L-Systems are perhaps the most familiar and developed tool for designers. L-systems portray plant branching through recursion that follows grammatical rules, resulting in skeletal forms of plant morphology (Prusinkiewicz & Lindenmayer, 1990). In addition to these skeletal models, volumetric techniques to capture the organic complexity of plant forms have been developed through photogrammetry to voxel methods (Middleton et al., 2022; Zhang & Hao, 2023). Complex forms of these procedural models found in the plant science disciplines incorporate growth, resource availability, and stochastic processes (often through agent-based modeling) with architectural models. These are described as Functional-Structural Plant Models and have been highly developed for production species like agricultural crops (Vos et al., 2010). Digital simulations of plant behavior have been proposed for green roofs (M. White et al., 2019), and modeled at the species scale (M. G. White et al., 2022). Predictive machine-learning modeling of tree branching response to pruning has also been explored (Shu et al., 2024). In the context of trees, tree information modeling has been proposed as a conceptual parallel to building information modeling, in order to standardize information and methods among various plant species, human objectives, and spatial contexts (Shu et al., 2022). The application of these types of models to applied architectural contexts has not occurred to the knowledge of the authors.

Architectural precedents that engage both plant morphological training and design computation are limited. A notable example includes Baubotanik (Ludwig, 2016). The initiative's goal is to develop a system of living structures in cities, where trees have a broader range of functions in the built environment, including acting as load bearing components. From this research, numerous insights have been assembled about their architectural potential and limits. For example, the first Baubotanik installation, a footbridge, contained diagonal trees for supports. These did not survive over time, perhaps due to graviomorphic deflection – when plant growth is forced from its natural direction (typically upwards), growth tends to slow, and senescence may occur. Another realization is that self-thinning (i.e., death) will occur, particularly as plants grow and some are outcompeted. Within this observation is emergence and uncertainty, driven in part by the unpredictable interactions of plants and their environments.

Flora robotica was a consortium initiative to "develop and investigate closely linked symbiotic relationships between robots and natural plants and to explore the potentials of a plantrobot society able to produce architectural artifacts and living spaces" (Hamann et al., 2017). A series of experiments and installations in this space were produced spanning a range of approaches. Most notable for this paper is their robotic node trellis system, which focuses on phototropism as a manipulatable design element (Wahby et al., 2018). The robotic node project investigated how a vining plant (common bean; *Phaseolous vulgaris*) responded to variable light as a growing stimulus. A series of light emitting IoT devices were attached to a trellis at junction points. Red wavelength light is shown at baseline, while blue wavelength is used as an attractor (plants' tropisms prefer blue light). IR Proximity sensors in the nodes detect plant growth tips within 5 cm. Experiments "demonstrate the ability of the nodes to shape climbing bean plants, steering the plants' binary decisions about growth directions as they navigate" – a type of plant agency. The application goal would be trellis systems that self-organize and self-repair based on different environmental and plant conditions, as well as algorithmic control of the nodes.

4.5 Methods

To expand the computational knowledge base of plant growth in architecture, the researchers conducted horticultural experiments with living plants and compared this data with predicted models of plant behavior. Perennial, woody vegetation like trees can take years to grow and show change, presenting a challenge for understanding plant responses. To accelerate knowledge production, fast growing annual agriculture crops were selected as model species. These plants represented a range of different growth habits (herbaceous ground vine, grass, single stemmed erect flower, and climbing vine), which would ideally provide insight into a broader range of plants beyond the modeled species. Species selected were common beans (*Phaseolus vulgaris*), corn/maize (*Zea mays*,), annual sunflowers (*Helianthus annuus*), and winter squash (*Cucurbita pepo*). Moreover, three of the selected species (corn, beans, and squash) are traditionally grown as part of an indigenous American agroecological co-planting – the Three Sisters (a.k.a. Milpas). This co-planting also often includes sunflower plants.

Prior to European colonization of the Americas, the Three Sisters was thought to be the dominant form of continental agriculture (Hart, 2003). In this multi-species planting complex, each plant plays a specific functional and architectural role. For example, corn provides a load bearing trellis for beans (a “beam”) while squash acts as a ground cover (a “floor” or “roof”; Fig. 22).

Figure 23: Diagram of the Three Sisters co-planting; Three sisters planted

The Three Sisters thus provides an extended metaphor for exploration of the architectural “tectonics” of plants. For this investigation, researchers drew inspiration from the traditional Wampanoag “Mound” technique (Pleasant, 2006). Beyond the computational questions explored through this research, the investigators aimed to honor this traditional ecological knowledge of indigenous American societies, while sharing that wisdom with current and future generations. Moreover, the unique cultural context of the indigenous polyculture system provides a theoretical opportunity for metaphysical exploration into plant ontology and the role of design computation.

Experimental Design

Based on preliminary growth experiments with the four plant species, specific computational-derived armatures and associated physical/morphological questions emerged that were suited to the behavior of each plant species (Fig. 23).

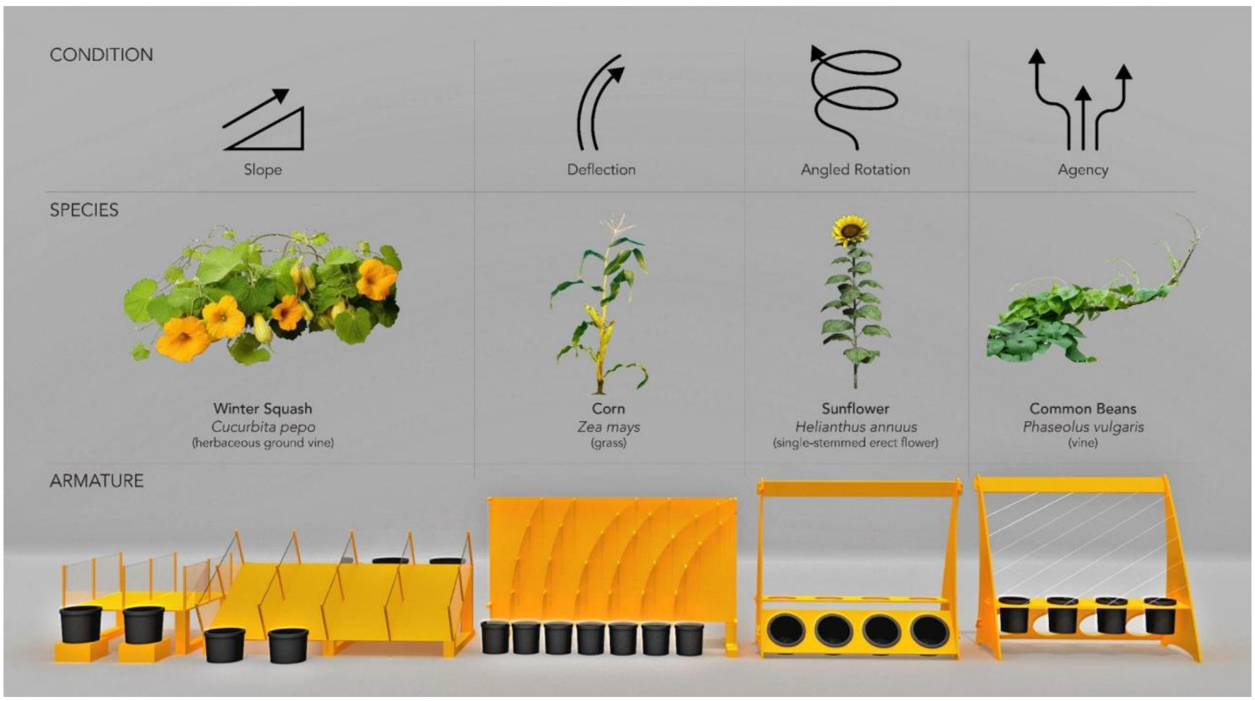


Figure 24: Diagram of plant growth conditions with associated species and armature designs

Horticulture research was conducted at Blandy Experimental Farm & State Arboretum of Virginia greenhouse over 2022-23 (Figs 11-14), as well as at local elementary school as part of an associated research study exploring human-plant engagement. Plants were grown in potted containers to facilitate manipulation and reached approximately 4’ (1.2m) in height/length. To isolate individual plant behavior, species were grown separately (not in the typical Three Sister co-planting design). Plant growth armatures explored distinct modeling questions:

Figure 25: Armatures for Slope (squash), Deflection (corn), Angled Rotation (sunflowers), and Agency (beans) in situ

Slope (Squash / *Cucurbita pepo*): Slope simply represents the angle of terrain, such as a roof. How does slope (positive and negative) affect overall plant morphology and rate of growth of a herbaceous ground vine? These were explored with a slope armature representing three slope conditions: 0° (control condition), -30° and 30°, with the prediction that a negative slope would produce greater plant growth due to gravity.

Deflection (Corn / *Zea mays*): Deflection represents the redirection of plant growth due to external materiality from a preferred upright direction, such as an arch. What effect do different growth deflection intensities have on morphology and overall rate of growth? These were explored with corn grown through clear PET channels representing different degrees of deflection, along with a control condition without deflection. Deflection conditions were arcs defined by circles with varying radius: low deflection / radius = 8’6” (2.6m); medium deflection / radius = 5’0” (1.5m); high deflection / radius = 4’2” (1.3m). It was predicted that as deflection increased, plant growth would decrease due to graviomorphic deflection.

Angled Rotation (Sunflower / *Helianthus annuus*): Angled rotation represents a shifting of plant positioning, thus inducing gravitropism and phototropism. How does angled rotation affect plant morphology and growth? Single stemmed erect sunflowers were grown in angled armatures (45°) and rotated weekly in two conditions: 90° and 180°. It was predicted that both conditions would result in similar growth rates, with the 90° turn producing a corkscrew growth pattern and the 180° producing a planar zig-zag growth pattern. A control condition was not incorporated for this armature.

Agency (Beans / *Phaseolus vulgaris*): How do plants respond to free growth compared to training? This was explored through a diamond-grid trellis armature where vining plants could “choose” either right or left. One set of bean plants were allowed to independently select their path (the control condition), while others were given a trained pattern of alternating left and right moves. It was predicted that there would be no biomass growth difference between both conditions, but more geometric structure in the trained plants.

Measurements

Two-dimensional (2D) and three-dimensional (3D) measurements of growth were documented via timelapse photography. These images were digitized and compared to predicted models of ideal plant behavior. For corn, squash, and beans, which were all grown in 2D armatures, measurements were taken through time-lapse photography at weekly time intervals during an 8-week period. The 2D visible plant biomass at each stage was measured through ImageJ, an open-source image processing software. For each plant and its treatment conditions, green pixels were selected through manual image thresholding to calculate the 2D visible plant biomass. Among all plants, every condition had at least two replicates and these were averaged. Total visible plant biomass was compared at three time intervals during the growing period. Additionally, since the initial growth starting point varied among each individual plant, a rate of weekly growth was measured via the formula: “Rate of Weekly Growth = New Weekly growth – Previous weekly Growth”.

For sunflowers (angled rotation), which represented a 3D measurement over time, weekly photographic measurements were not possible because this would require leaf removal for effective documentation and kill the plants. Instead, the rotational point on the plant stem where new growth occurred was measured at each weekly turning interval. At the end of 8 weeks, leaf material was removed so that plant stems were clearly visible, and photogrammetry models were created using Autodesk Recap. For each of these geometric measurements, above ground plant biomass was digitally traced and compared to predicted plant growth geometries.

4.6 Results & Discussion

Results for each experimental condition (slope, deflection, angled rotation, and agency) are presented in Fig. 15-18. For slope (squash) and deflection (corn), plant growth at different time points during the 8-week period is visualized, along with an estimation of biomass. Similarly for beans (agency), biomass growth is graphed over the three time points. However, only the central stem of each plant is visualized due to the complexity of the bean plants. Finally, for sunflowers (angled rotation), only the final biomass is graphed due to photogrammetry constraints. Additionally, photogrammetry models of plants in elevation and section are both presented.

Slope (Squash / *Cucurbita pepo*): The results of this experiment did not follow the predictions that a negative slope would produce greater growth due to gravity. Instead, the positive slope resulted in the greatest rate and total biomass increase, followed by the negative slope. It is unclear why this occurred, although as an herbaceous ground vine with tendrils, squash may be adapted towards climbing up slopes. At the same time, the negative slope did produce the longest plants, suggesting a role for gravity in extending the length of plant growth. Notably, the 0° control condition produced the least biomass, but the reasons for this are unclear. A future study with more replicates would help elucidate this phenomena.

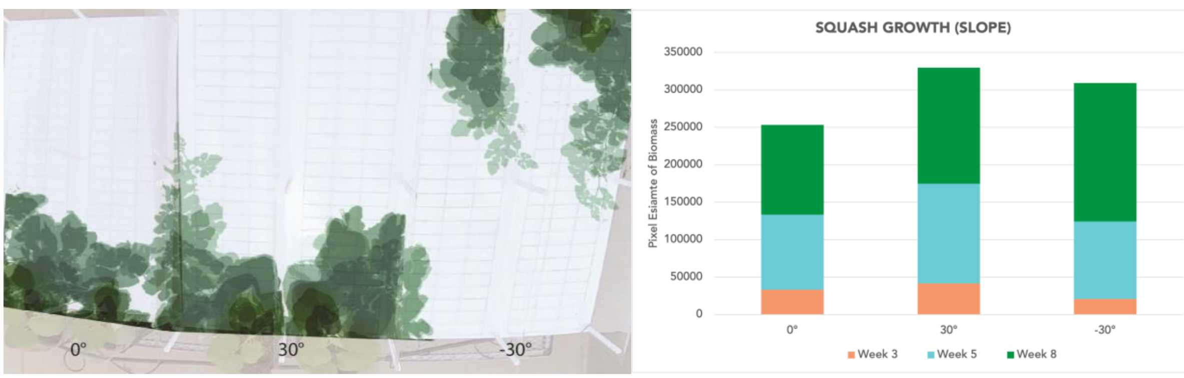


Figure 26: Results from slope experiments using winter squash

Deflection (Corn / *Zea mays*): The results of this experiment did follow predictions; as deflection increased, biomass and rate of growth decreased. This concurs with previous research into graviomorphic deflection, which has shown plants will often slow their growth when unable to grow in a preferred upright form (Ludwig, 2016) (Fig. 29). The no deflection control condition (data not shown) did produce greater biomass and overall length than all deflected conditions which was likely a result of corn's strong preference for vertical growth.

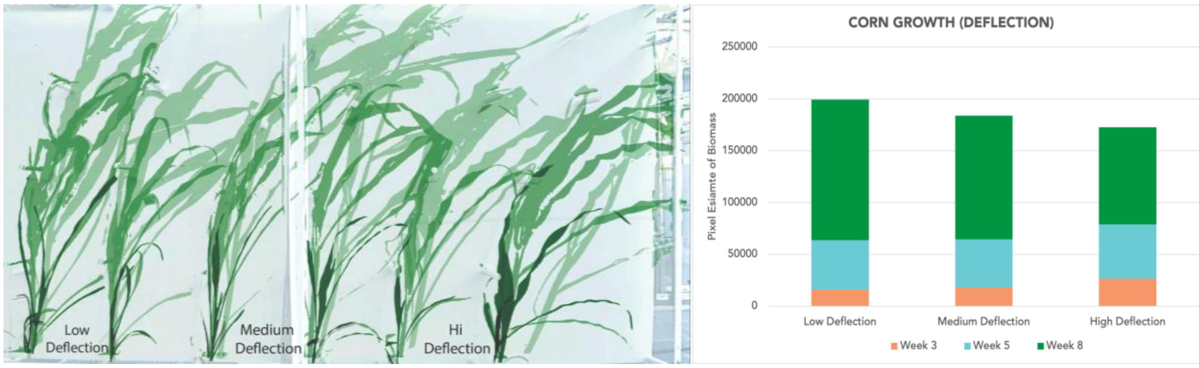


Figure 27: Results from deflection experiments using corn

Angled Rotation (Sunflower / *Helianthus annuus)*: The angled rotation experiment produced unexpected results. From a geometric perspective, the plants that were turned 90° weekly resulted in more consistent forms akin to a corkscrew pattern, while the plants turned 180° weekly did not produce a strong planer zig-zag pattern. This might be because 180° is too dramatic of a turn for the plants to effectively respond, while 90° allows more time for the plants to adjust to the gravitropic and phototrophic effects. At the same time, biomass was greater in the 180° condition, suggesting that while these plants were not able to successfully turn, they were more successful at sending resources into biomass.

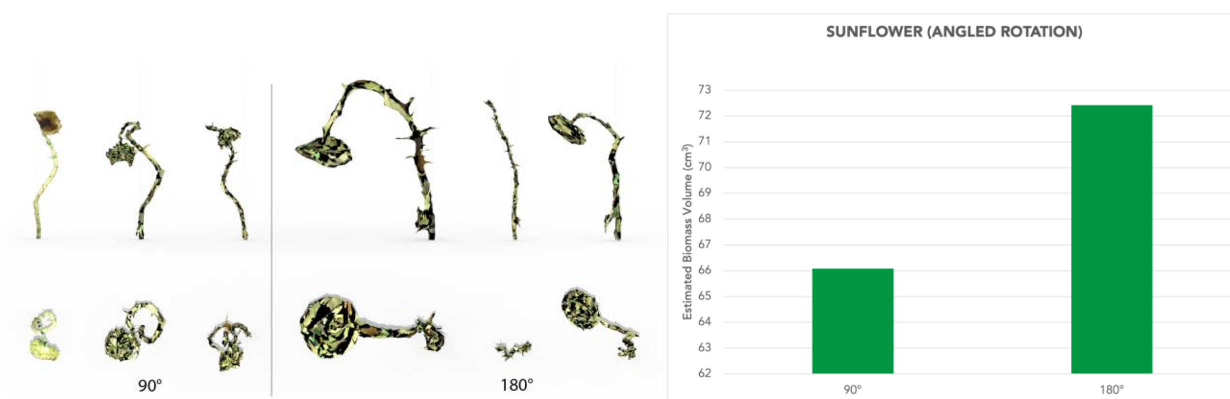


Figure 28: Results from angle rotation experiments using sunflowers

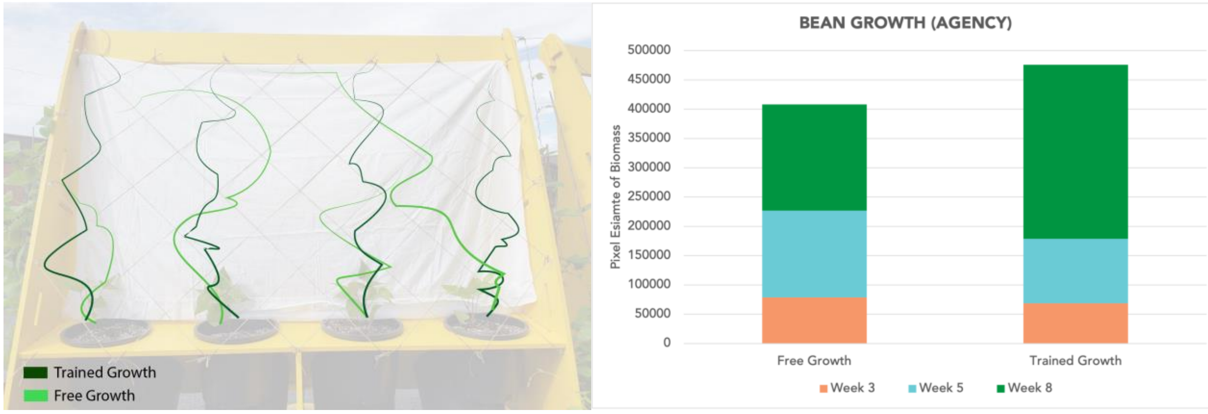


Figure 29: Results from agency experiments using common garden beans

Agency (Beans / *Phaseolus vulgaris*): Trained growth resulted in a greater estimated biomass compared to free growth plants. This implies the human process of training plants can increase their productivity. Concomitantly, the free growth plant produced more irregular geometries compared to trained plants, where once plants turned (left vs right), they tended to continue that directionality.

Research Limitations

Taken together, these novel methods and results demonstrate that plant growth responds to spatial interventions in diverse ways, sometimes unexpectedly. Yet, as with any study, there are some limitations and constraints. First, to expedite knowledge production, research occurred with annual plants, which were mostly fruit/vegetable producing species and with relatively few experimental replicates. It is unclear if the insight from these model species is transferable to other species and growth conditions. Additionally, since these were annual plants, pruning was not employed as an intervention. Pruning is a commonly utilized technique in the shaping and management of perennial woody plants like trees. Future studies should explore this in more detail, perhaps with biennials or fast-growing woody perennial plants. Additionally, to analyze plant growth, measurements were only taken for visible plant biomass – effectively not measuring the depth of plant biomass. A more accurate measurement would have been leaf area index which accounts for plant growth in the Z dimension. From a digital-physical modeling perspective, the dynamic behavior of plants could be more closely modeled in real time. At the same time, the predicted models employed for this research were simple geometric forms and morphologies. More sophisticated models that draw from functional structural plant modeling could be incorporated (Vos et al., 2010).

Figure 30: Example corn plant, grown in a deflecting armature

4.7 Conclusions

Computation could provide insight into multispecies design in the built environment, including with plants, with implications for a range of nature-based urban solutions such as greenwalls, roofs, street trees, and – the specific context of this dissertation – biophilic tactical urbanism. As a starting point, this paper sought to test methodological frameworks for "Computational Cultivation" to build the vocabulary and toolbox, providing a foundation for future studies of plant-architecture entanglement. Most relevant to the designer from this study is that plant performance, in this case growth and morphology, acts in response to architectural interventions in diverse, species and built form-specific ways. This emerges in part due the difference in temporal scales between humans and plants. The digital/ physical sensing and responding approaches tested here provide a window for human perception of plant time, which could lead to more robust and rapid plant/built environment model generation. Future design research should build on the insights gleaned, and further incorporate responsive plant dynamics, as seen with beans and agency and Flora Robotica (Hamann et al., 2017).

Additionally, the current study considered multispecies design from a single-species, abstracted lens focusing on morphology. Understanding the myriad potential interactions between multiple species, the built environment, and broader ecology on site will require more complex modeling and sensing strategies beyond this scope. Moreover, computationally assessing the downstream ecological impacts of multispecies plant design on biodiversity (e.g. wildlife), resource usage (e.g. water), and climate in real-world contexts deserves future attention.

Chapter 5 [Ecology]: Biophilic Tactical Urbanism - Experiments between Temporary Architecture and Multispecies Design

5.1 Chapter Integration

This chapter investigates the design and effects of a 1:1 BTU intervention on surrounding ecology in an elementary school parking lot. The design choices that were made in the fabrication and cultivation of the BTU system are explored. From a science perspective, the impacts on insects (and spiders) and urban heat are examined. Insects serve as ideal "canaries in the coal-mine" for testing the immediate effects of temporary biodiversity on surrounding ecosystems. Equally, the impacts of temporary greening interventions like BTU on heat island effects have not been explored sufficiently, based on a literature review by the author This research occurred in parallel with research in Chapter 6 [Human Behavior], where children's

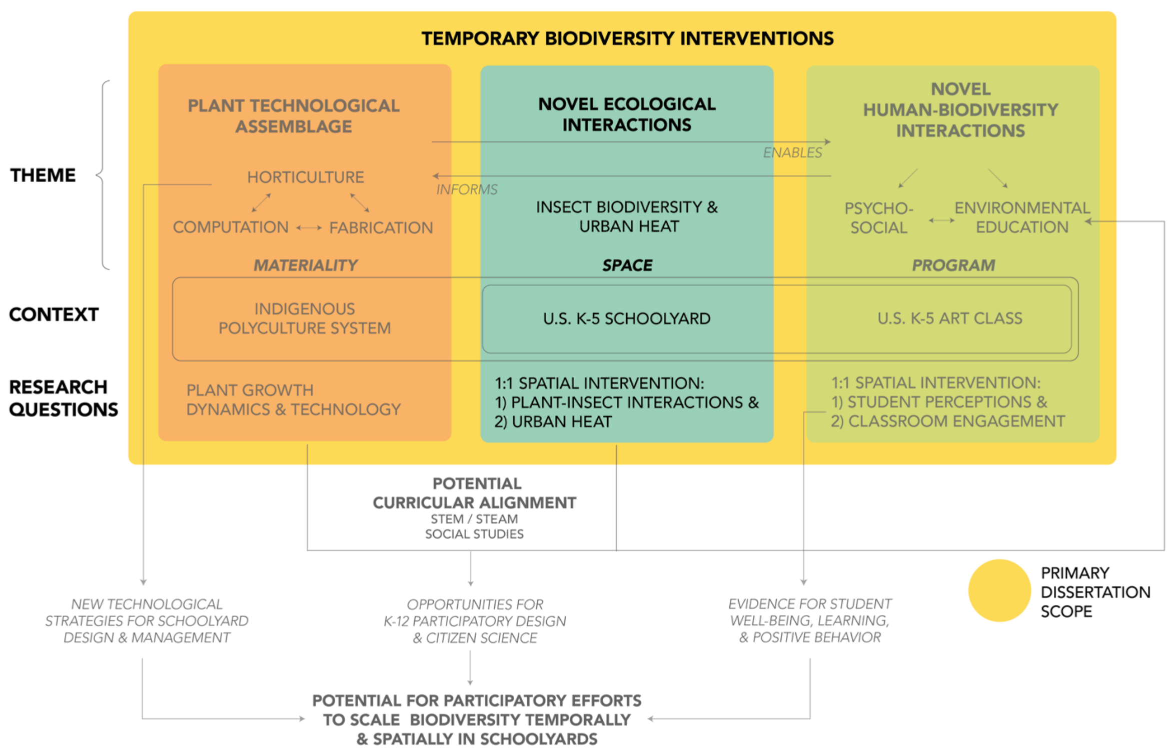


Figure 31: Interdisciplinary framework of dissertation – Ecology

perceptions of insects and other ecological elements were measured through participatory photography. The conceptual goal was to link the study designs for both chapters (actual biodiversity to perceived biodiversity), but that was not empirically attainable with the dissertation's scope. This manuscript is reprinted with minor revision from "Biophilic Tactical Urbanism: Experiments between Temporary Architecture and Multispecies Design" *Proceedings of Divergence In Architectural Research, 2024* with minor revisions.

5.2 Abstract

Tactical/temporary urbanism (T/t urbanism), the activation of public space through temporary interventions, has emerged as a common design strategy to promote longer-term positive shifts in the planning and formation of public spaces. The practice is typically positioned toward improving the human condition. This paper investigates how T/t urbanism might be expanded to a multispecies, "more-than-human" lens. How might T/t urbanism intersect with biodiversity in novel, scalable, and measurable ways to promote more sustainable, multispecies futures in the built environment? The term biophilic tactical urbanism is proposed as a design strategy and explored through 1:1 scale investigations and research experiments using a design science framework. This culminated in the development of a T/t urbanism system for plant ecologies: a low-cost, mobile, modular planter system for rapid deployment of biodiversity into new contexts. Five different design geometry/plant ecology concepts were developed, representing a range of biodiversity and programmatic opportunities. The intervention was deployed in the context of a public elementary school parking lot in the Mid-Atlantic U.S. This paper describes the results of this work on surrounding ecological systems, specifically insects as a metric of multispecies impact. Additionally, the intervention's effect on urban heat was

examined. Results indicate that temporary biodiversity can have a significant effect on the broader nature of public spaces, even at small spatial/temporal scales.

5.3 Introduction

Biodiversity & Cities

Biodiversity is in crisis at a planetary scale. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), “around 1 million animal and plant species are now threatened with extinction, many within decades, more than ever before in human history” (IPBES, 2019). Cities have a unique role in the biodiversity crisis, even though the ecologies of urban environments have been historically understudied compared to rural and “wild” places (Gaston, 2010). More recently, there has emerged a shift toward recognizing that cities are critical for addressing global and regional biodiversity challenges. Rather than being ecological wastelands, some scholars of biodiversity increasingly see cities as a “frontline” in biodiversity conservation (Lambert & Schell, 2023; Spotswood et al., 2021).

Globally, it is estimated that the built environment land cover will increase by “4.5 times by the year 2100 under middle of the road estimates” (Gao & O’Neill, 2020). Yet, this land use change masks the highly productive quality of cities. Many urban environments are found in ecosystems with inherently high endemic biodiversity (e.g., along rivers, estuaries, etc.). Patterns of human development often disrupt ecosystems in these areas, resulting in habitat and species loss in ecologically rich environments. Meanwhile, cities may support some species that can adapt to urban environments in unique and unexpected ways, producing novel, no-analog ecosystems (Alagona 2022). Concomitant with these ecological trends, the world is increasingly urban, with more than 55% of the world’s population living in urban areas (Gao & O’Neill, 2020). With more humans living in cities, human connectedness to nature (e.g., biodiversity) is also thought to be declining, described by some as an extinction of experience (Soga & Gaston, 2016); people may be less likely to have direct contact with ecological systems and associated species. This presents a significant challenge to biodiversity goals because positive environmental experiences are a strong predictor for developing pro-environmental values and behavior later in life (Wells & Lekies, 2006). Despite these challenges, new strategies to support urban biodiversity are emerging through interdisciplinary fields like urban ecology and design writ large.

Design with Biophilic Tactical Urbanism

There are many nature-based solutions for urban biodiversity, ranging from city-wide efforts, such as ambitious urban re-designs for green and blue spaces, as seen in cities like Paris (Moore, 2023), marquee architectural provocations like the Bosco Verticale in Milan and Gardens by the Bay in Singapore, as well as smaller-scale strategies occurring across urban contexts like green walls, green roofs, rain gardens, Miyawaki forests (Miyawaki, 1998), etc. It should be noted that for many of these solutions, biodiversity is often an incidental benefit/objective to the numerous ecosystem services provided. For example, planting trees in cities reduces urban heat while simultaneously providing habitat for other species (L. E. O'Brien et al., 2022).

Achieving the long-term, relative permanence of the above "design for biodiversity" strategies require significant resources and community buy-in, which may present challenges. In response, this paper explicitly considers temporary and tactical low-cost strategies to shift urban design toward biodiversity as a potential transitional approach that could lead to more permanent interventions. Among the many terms to describe this method include insurgent urbanism (Hou, 2010), temporary urbanism (Bishop & Williams, 2012), tactical urbanism (Lydon & Garcia, 2015), bottom-up urbanism (Arefi & Kickert, 2019), and pop-up urbanism. Collectively these approaches are referred to here as tactical/temporary urbanism, or T/t urbanism (Stevens & Dovey, 2022). T/t urbanism has emerged as a ubiquitous global trend in urban design, with projects ranging from transportation (e.g., bike lanes), food production (e.g., guerilla gardens), and public space (e.g., parklets). These test-bed interventions often, but not always, serve as primers for more permanent changes to the built environment by catalyzing public engagement in the design of public space. For example, the conversion of New York City's Times Square from auto-centric to pedestrian-centric travel began with simple T/t urbanism interventions, like outdoor furniture and food vendors (Lydon & Garcia, 2015).

Not surprisingly, these interventions tend to focus on the needs and wants of humans rather than non-human actors, though the two are not mutually exclusive. Notable exceptions that explicitly focus on biodiversity include the American Society of Landscape Architecture's 2023 Park(ing) Day, which nationally focused on pollinator-based T/t urbanism (ASLA, 2023), a pop-up grassland research study in Melbourne, Australia (Mata et al., 2019; Fig. 30) As a novel

Figure 32: Examples of biophilic tactical urbanism. Clockwise from top left: "Archipelago" by Jerónimo; "Bee Connected" by The Spatial Morphology Group at Chalmers; "Tiles" by Thibault Faverie, Paris France; "Tactical Urbanism" in Barcelona, Spain; "Build a Better Block" in Dallas, TX; "Layfette Elementary School Science Garden & Outdoor Classroom" in Seattle, WA

intersection of T/t urbanism and biodiversity, the authors propose the term biophilic tactical urbanism (BTU)—low cost, above-ground interventions to temporarily shift urban space toward biodiversity. This term centers on plants as the foundation for all other terrestrial food webs.

Measuring Impacts of Biophilic Tactical Urbanism: Pollinators and Beyond

An empirical critique of T/t urbanism is that impacts are difficult and/or rarely measured, both in the temporary period of installation and afterwards. To address this in the context of ecology and BTU, terrestrial invertebrate species (insects and spiders) including pollinators like bees and butterflies provide a unique and compelling metric for ecological impacts. Insects are the most ubiquitous and diverse animals on the planet (van Klink et al., 2020) and are bioindicators—canaries in the coal mine—for a range of human impacts on the environment (McGeoch, 1998). They are often the first animals to colonize new and/or disturbed habitats, analogues to the spaces that BTU could provide, and are highly responsive to spatial and temporal shifts in vegetation.

From a human benefit perspective, invertebrate pollinators have an outsized role in society and broader ecological systems. Most notably, 35% of global crop production requires pollination (Klein et al., 2006). From a non-human perspective, insects and other invertebrates often serve as a critical second tier for most food webs, between plants and larger animals. For example, across the planet, most species of birds are either completely or partially insectivorous, relying heavily on insects for their diet (Nyffeler et al., 2018). At the same time, terrestrial insect populations are experiencing widespread decline due to anthropogenic forces, with an estimated average decline of 9% per decade driven primarily by land-use changes based on meta-analysis (van Klink et al., 2020). Finally, invertebrates like insects also represent an understudied (Titley et al., 2017) and often underappreciated/feared taxa of organisms compared to vertebrates like mammals, birds, etc. (Lockwood, 2013). Invertebrates thus provide a unique taxon for investigating underexplored and challenging questions of human perception and values of the non-human world.

Terrestrial invertebrate research in the urban context represents a small but growing domain of research, and one in which T/t urbanism and BTU could provide meaningful insights. Cities are a mosaic of built environments with interspersed islands of habitat. Drawing from the Equilibrium Theory of Island Biogeography (ETIB) (MacArthur & Wilson, 1969) MacArthur and Wilson 1969) and subsequent landscape ecology theories (Forman & Godron, 1991), the size, shape, and relative isolation of habitat patches in larger spatial matrices could drive the species richness and overall diversity of invertebrates in the built environment (Fig. 31).

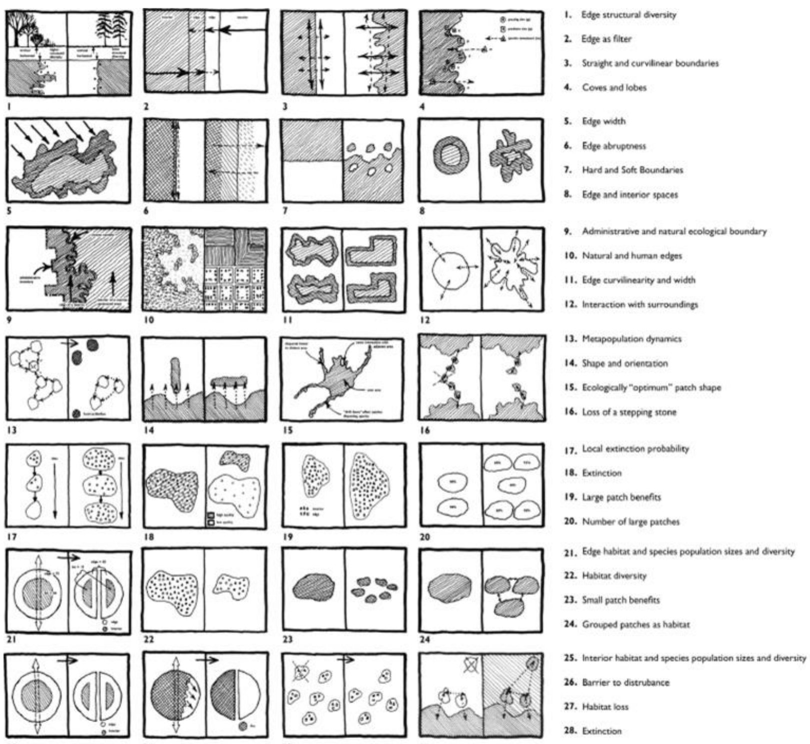


Figure 33: Landscape ecology typologies, providing spatial inspiration for micro-scale BTU interventions (Dramstad et al., 1996)

Theoretical frameworks using patch/matrix spatial relationships for understanding insects in the built environment have been supported via meta-analysis, though with many unanswered questions (Fattorini et al., 2018). There may be temporal and taxa-level differences between types of insects. For example, a large-scale study comparing urban to rural insects found that urban areas supported bees, but not flies and butterflies, driven by flower richness (Theodorou et al., 2020). BTU installations could act as artificial, manipulatable habitat patches, allowing for greater control and insight into the relationship between urban biodiversity and urban design—insight that might extend beyond the impermanence of T/t urbanism to more permanent design solutions. To date, only one published paper has focused on the impact of BTUs on invertebrate populations (Mata et al., 2019) to the knowledge of the authors. In this study, researchers created a temporary "grassland" (~100m^2) with 56 plant species, representative of native grasslands in the study's region. They found significant increases across all species groups over a six-week period.

Spatial & Programmatic Context

The research was situated in the spatial and programmatic context of a K–5 elementary schoolyard in the Mid-Atlantic region of the US. Typical US school environments are relatively homogenous landscapes whose land cover are dominated by turf and pavement (Schulman & Peters, 2008)—effectively, biodiversity deserts. A similar trend was found in the study region (Barnes & Barnes, Audrey, 2023). Researchers developed a partnership with Keister Elementary School, whose design consists of a central building surrounded by turf, pavement, and sporadic tree cover (Fig. 32). Administrators allowed the deployment of a BTU intervention in the form of an outdoor nature-based learning environment in a parking lot and adjacent field and within a short walking distance of the building from August through October of the 2023–2024 school year.

Figure 34: Aerial view of Keister Elementary School; site of BTU classroom before installation.

5.4 Design Questions

Central to the potential of BTU in supporting downstream biodiversity such as invertebrates are the constructed plant communities that constitute the intervention. Recognizing the dearth of knowledge in this arena, testing a spectrum of temporary plant communities could provide a greater range of insight. At the same time, growing plants in mobile containers has ecological limitations regarding plant size, soil moisture, and overall viability. For example, large trees would not be practical. Additionally, planting design could be informed by the specific programmatic focus on K–5 education and associated curricular alignment. T/t urbanism approaches typically value materiality and assemblage that is low-cost, DIY, and scalable (Lydon & Garcia, 2015) and have not been deeply explored for modular planting designs. These design opportunities and constraints can be reframed as:

Q1: What plant communities would be best suited to BTU design in the socio-ecological context of K–5 schoolyards in the Mid-Atlantic US?

Q2: What material assemblages, geometries, and scales of BTU would be best suited to the socio-ecological context of K–5 schoolyards in the Mid-Atlantic US?

5.5 Design Methods

Design research centered on 1) research and fabrication of a mobile architectural armature system for plant communities and 2) horticultural research into specific plant communities for integration into the armatures. For the armatures, a modular, configurable geometry was produced (Fig. 33-35). This design allowed for multiple spatial arrangements depending on need, including a green wall, façade, terrace, and pergola pole. These were designed to be hardware-free and flat-pack for ease of assembly, transport, and storage. The original designs intended for these to be constructed from sheet metal, but this proved to be cost prohibitive and would ultimately limit the scalability and DIY potential of the design. Consumer-grade, exterior-protected 4’x8’ plywood was used instead. Plywood was milled with a CNC router. Yellow was selected as a color because it has been shown to attract a range of insects (Prokopy & Owens, 1983) and is also a color associated with human attention. A total of 9 armatures were fabricated, each ~2.5 m^2 (26 ft^2) for a total area of ~22 m^2 (237 ft^2). Collectively, the armatures were arranged in the school parking lot to emulate a semi-enclosed outdoor learning environment.

Figure 35: BTU plant armature system models in perspective

Figure 36: BTU in rendered section

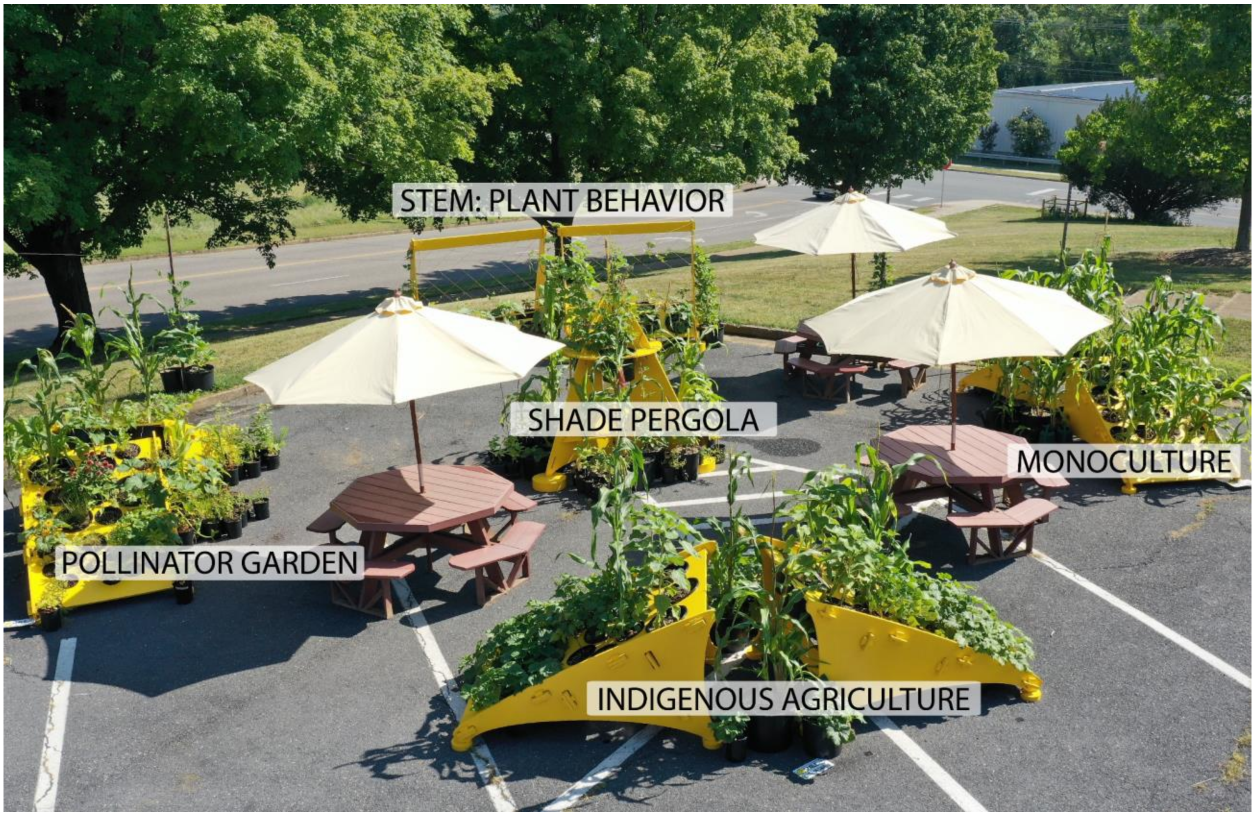


Figure 37: BTU deployed at Keister Elementary School

Figure 38: Biodiversity conditions for the intervention: low (monoculture), mid (indigenous polyculture), and high (pollinator meadow).

5.6 Scientific Questions

Scientific-based research questions focused on the impact of the designed BTU installations on terrestrial invertebrates and urban heat. What impact does BTU have on invertebrates like bees and butterflies? Are there differences in invertebrate species richness between different BTU biodiversity conditions? Are invertebrates using the temporary habitat for food, specifically floral resources, or not? These questions can be framed as hypotheses:

H1: As BTU plant richness increases, invertebrate family richness will increase.

H2: As BTU plant richness increases, invertebrate family richness will contain more individuals demonstrating pollination behavior (i.e., visiting a flower).

In addition to these biodiversity questions, the effect of BTU on urban heat was a secondary interest in the study. Plants can provide shade for open spaces and cooling through evapotranspiration. Research suggests that different green infrastructure types (e.g., street trees, green roofs) can affect urban heat differently at the micro spatial scale (Zölch et al., 2016), similar to the scale of typical T/t urbanism installations. The researchers did not find any existing research studies on the impact of T/t urbanism on urban heat. In the absence of existing background research, the following hypothesis emerged:

H3: BTU interventions will have a negligible or a small effect on urban heat at the micro spatial scale.

5.7 Scientific Methods

Visual surveys of invertebrate biodiversity richness were conducted at the site 10 times over a four-week period between August 22–September 25, 2023. These surveys occurred on fair weather days between 10:00 and 15:30. The average air temperature across all survey days was 25°C (77°F). The three biodiversity conditions (high, medium, low) were surveyed consecutively. Surveys were conducted using a photographic sampling technique, where the presence of any invertebrate family was photographed over a 5-minute sampling window. This data represented family richness—simply the presence of a family. Family-level identification was conducted because species and genus-level ID was not possible for many observations. If different individuals from a family occurred multiple times, it was only photographed/counted once (Fig. 37). Images were coded to the family level using software (Picture Insect App) and spot checked by a professional entomologist. If an invertebrate could not be effectively identified at the family level, it was not included in the analysis. In addition to invertebrate family richness data, invertebrate presence on flowers was also coded as a metric of potential pollination activity. Results from each biodiversity condition (low, medium, high plant biodiversity) were analyzed with a repeated measures ANOVA analysis using R statistical software and tested for statistical assumptions. To calculate a more holistic measure of overall biodiversity, the species families observed for each sample day were summated over a percentage of total species families observed during the entire study period. This measure is described as Composite Invertebrate Family Richness. For example, if Apidae (common bees) were observed on seven sampling days, they were given a value of seven. For temperature data, ground level temperatures using an infrared thermometer were measured on September 6, 2023, at mid-day, when ambient temperatures were 34°C (93°F). Temperature readings were taken throughout the installation and surrounding area.

Figure 39: Example images from invertebrate survey. Clockwise from top left: bumble bee (Hymenoptera), grasshopper (Orthoptera), skipper butterfly (Orthoptera), wasp (Hymenoptera), stink bug (Hemiptera), golden soldier beetle (Coleoptera).

5.8 Results

Invertebrate Family Richness

Hypothesis 1 (As BTU plant richness increases, invertebrate family richness will increase) was supported. Mauchly's test of sphericity indicated that the assumption of sphericity could be rejected, hence the assumption had not been violated ($\chi2(2) = 0.921$, $p = 0.631$). The repeated measures ANOVA test indicated that there is a significant difference in invertebrate family richness between the different plant biodiversity conditions ($F (2,18) = 9.99$, $p = 0.001$), with a mean of 6.5 for low biodiversity (monoculture), 8.1 for mid biodiversity (indigenous polyculture), and 11.6 for high biodiversity (pollinator meadow). The post-hoc paired t-test test using a Bonferroni correction ($\alpha = .017$) indicated that the means of the following pairs were significantly different: low and high biodiversity conditions, as well as mid and high biodiversity conditions. No difference was found between low and mid biodiversity conditions. See Fig. 6 and 7 for further descriptive statistics regarding the distribution of invertebrates among phylogenetic families.

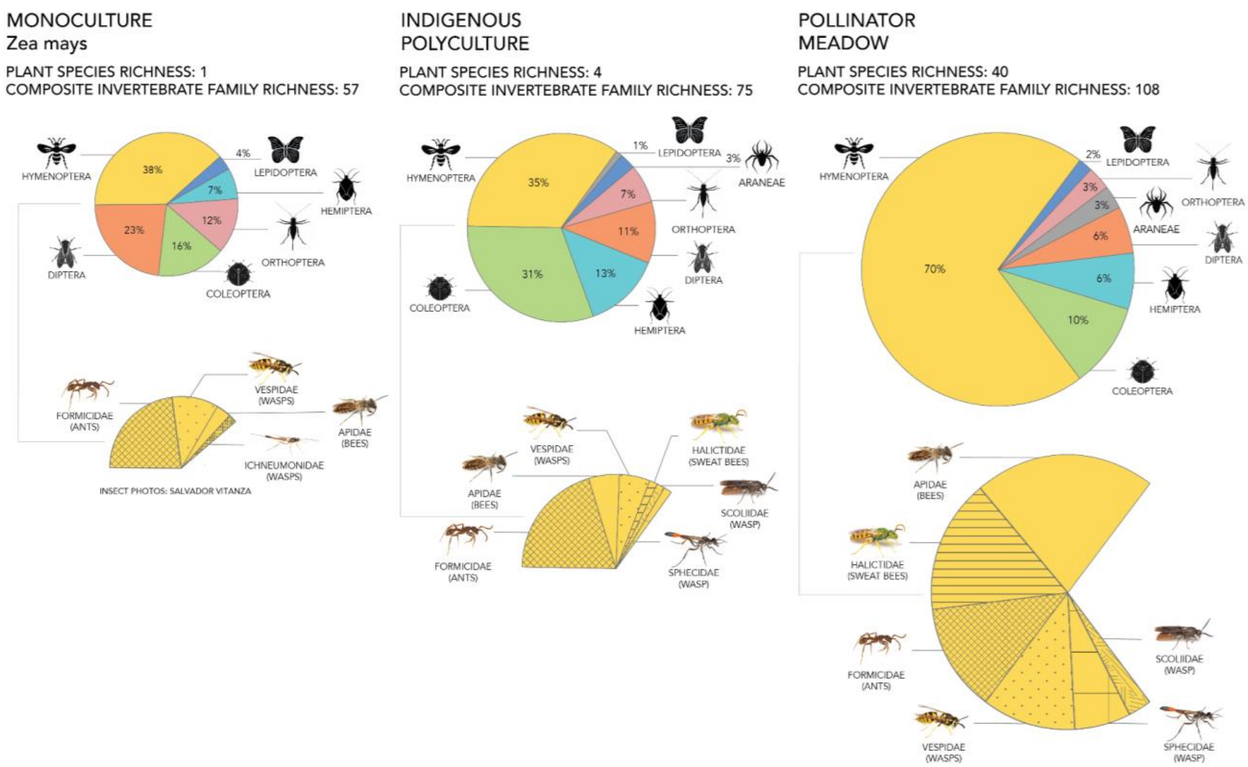


Figure 40: Invertebrate species family richness among three different plant biodiversity conditions. Pie chart sizes represent the relative number of family observations and are visually normalized between plant biodiversity conditions.

Hypothesis 2 (As BTU plant richness increases invertebrate family richness will contain more individuals demonstrating pollination behavior [i.e., visiting a flower]) was also supported.

Mauchly's test of sphericity indicated that the assumption of sphericity had been violated ($\chi2(2) = 8.108$, $p = 0.017$), and therefore a Greenhouse-Geisser correlation was used ($\varepsilon = .611$).The repeated measures ANOVA test indicated that there is a significant difference in the invertebrate species richness between the different plant biodiversity conditions ($F(1.22, 11) = 31.7$, $p < 0.001$), with a mean of 0.5 for low biodiversity (monoculture), 0.5 for mid biodiversity (indigenous polyculture), and 5 for high biodiversity (pollinator meadow). The post-hoc paired t-test test using a Bonferroni correction ($\alpha = .017$) indicated that the means of the following pairs were significantly different: low and high biodiversity conditions, as well as mid and high biodiversity conditions. No difference was found between low and mid biodiversity conditions.

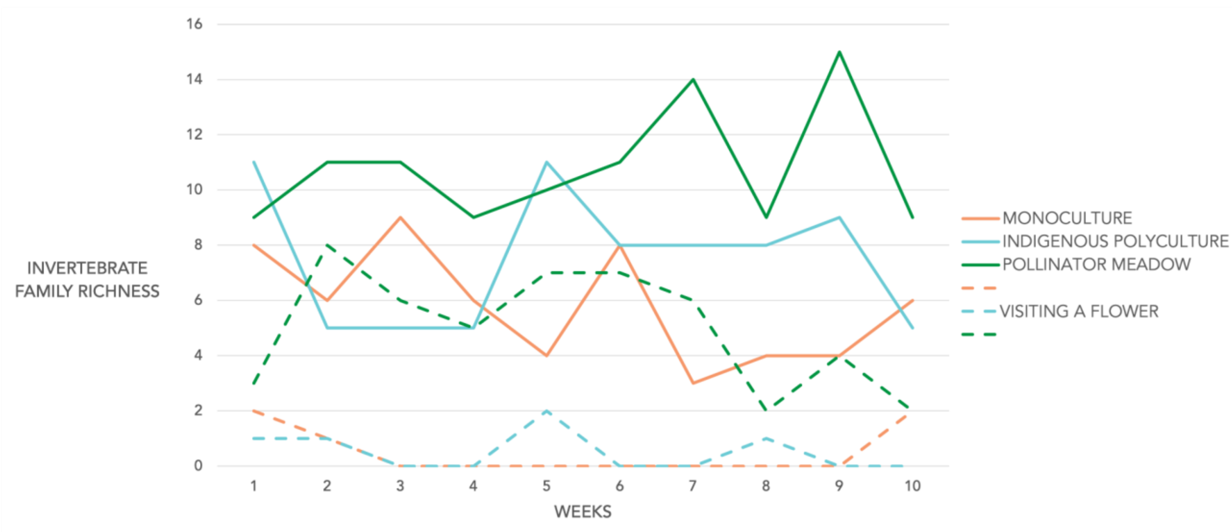


Figure 41: Invertebrate family richness over the study period, including demonstration of pollination behavior (present on flower).

Urban Heat

Infrared thermal measurements revealed significant surface heat in pavement areas 62°C (143°F) compared to ambient air temperature measures of 34°C (93°F), an increase of 28°C (50°F) which was expected due to the thermal absorbing properties of pavement. The temperature on the pavement surface under the BTU interventions had a mean of 37°C (99°F) –

a drop of 24°C (44°F) compared to exposed parking lot areas. This was cooler than under table pavement where mean temperatures were 42°C (108°F) – a 5°C (9°F) drop for BTU armatures. **Hypotheses 3** (BTU interventions will have a negligible or a small effect on urban heat at the micro-spatial scale) was rejected. Results are shown in Table 2 and visually in Fig. 40.

Sampled Area	°C	Δ °C between Pavement & BTU Armature	°F	Δ °F between Pavement & BTU Armature
Ambient Temperature	34	-3	93	-6
Exposed Parking Lot	62	24	143	44
Pavement Under Table w/ Umbrella	42	5	108	9
Pavement Under BTU Armature	37		99	

Table 2: Mean temperatures comparisons at four locations in and around the BTU installation in summer

Figure 42: Temperature readings at the site during a day with ambient air temperature of 34°C (93° F).

5.9 Discussion

BTU appears to directly support habitat for more-than-human life. Invertebrate biodiversity (insects and spiders) followed a predicted pattern, where increasing plant biodiversity was associated with increased invertebrate family richness, which was statistically significant for the high biodiversity condition (pollinator meadow) but not between the low and mid biodiversity conditions. Species richness consisted primarily of insects. Even though spiders—the only non-insects observed—were not frequent, their presence and role as predators suggest more complex food webs were emerging within the intervention.

Increased insect family richness was most associated with the Hymenoptera order of insects: bees, wasps, and ants. This is notable because Hymenoptera species play an outsized role in pollination. Additionally, a statistical test of "insects on floral resources"—a metric for whether insects are acting as pollinators—showed a statistically significant effect for the high biodiversity condition compared to the low and mid biodiversity conditions. Moreover, the pollinating potential of different taxa in Hymenoptera is diverse, with insects like bees and wasp serving a much greater role in pollination than ants. Bees and wasps increased with increasing plant biodiversity, while ants were relatively consistent across the BTU biodiversity conditions. Interestingly, butterflies (Lepidoptera) were nearly absent from all conditions, and only one family was observed (Hesperiidae, skipper butterflies). The reason for this is unclear. Perhaps the temporal or spatial scale of the intervention was not large enough to attract these species. Alternatively, the broader environmental matrix around the site could have played an intervening role; there may not have been enough suitable habitat around the intervention to provide a source population of butterflies. Interestingly, even though the low and mid plant biodiversity conditions contained significantly less family richness, they were not barren of insects, which was surprising. This was most notable for the monoculture condition, which shows that even temporary, single species planting designs provide some habitat, albeit much less than multispecies planting designs. Urban heat effects were more dramatic than expected at the micro-spatial scale, with a very significant temperature differential between pavement and the interventions. This could have implications for the incorporation of plants into the built environment to address urban heat effects, both temporary and permanent.

5.10 Research Limitations & Future Directions

There are several limitations to the study from a scientific frame. First, each plant biodiversity condition was not spatially independent. There could be effects from one installation to another, like the combination of different biodiversity conditions in proximity being synergistic in the attraction of particular invertebrates. Second, while baseline data for the parking lots was collected (two species of ants observed), baseline data for the adjacent turf area was not collected. This would have provided more insight into the causative role of BTU. The presence of invertebrates like the golden soldier beetle (*Chauliognathus pennsylvanicus*) may have not been a response to the installation; rather, they may have already been present in the nursery stock. A future study should ensure that there are limited insects present in the nursery stock prior to installation. From a larger landscape frame, future research should explore large spatial and temporal scales for BTU interventions to better elucidate the theoretical relationships between this research and theories of island biogeography, landscape ecology, and population dynamics. For example, the effect of spatial scale is likely significant, and a future investigation should explore the effects of different sized interventions. Additionally, beyond biodiversity, the effect of BTU on urban heat at the micro-spatial scale provides a provocative avenue for future research.

From a design frame, this research attempted to capture the essence of ecosystems at small temporal and spatial scales—essentially abstractions of the real world, which involved trade-offs between “natural-ness” and the goals of T/t urbanism. As an example, the use of potted plants allowed for standard, commercially available nursery plants but resulted in limitations in the physical size of the armatures due to soil weight. Future research will explore novel methods for abstracting plant ecologies, such as hydroponic growth medium and the design of different plant communities beyond monoculture, indigenous polyculture, and pollinator meadow. Moreover, the triangular relationship of humans, non-humans, and BTU was not explored in this paper. How humans perceive and relate to temporary biodiversity installations is critical for linking the objectives of T/t urbanism strategy to policy objectives through applied research. This represents a critical linkage for understanding multispecies design, particularly in the context of children and environmental education, and will be examined in a future associated manuscript.

Chapter 6 [Human Behavior]: Biophilic Tactical Urbanism in an Elementary Schoolyard

6.1 Chapter Integration

This chapter explores the impacts of an BTU outdoor nature-based classroom intervention in an elementary school parking lot on student perceptions and classroom engagement through partnership with an art teacher. Building upon computational & horticultural research in Chapter 4 [Technology] and biodiversity research in Chapter 5 [Ecology], this paper in many ways represents a culmination of the empirical dissertation whereby the impacts of BTU on human experience were explored. Notably, two of the four plant research experiment conditions from Chapter 4 [Technology] (angled rotation: sunflowers; agency: common beans) were incorporated in this intervention, though they were not explicitly part of the human behavior study. This chapter is reprinted with minor revisions from "From

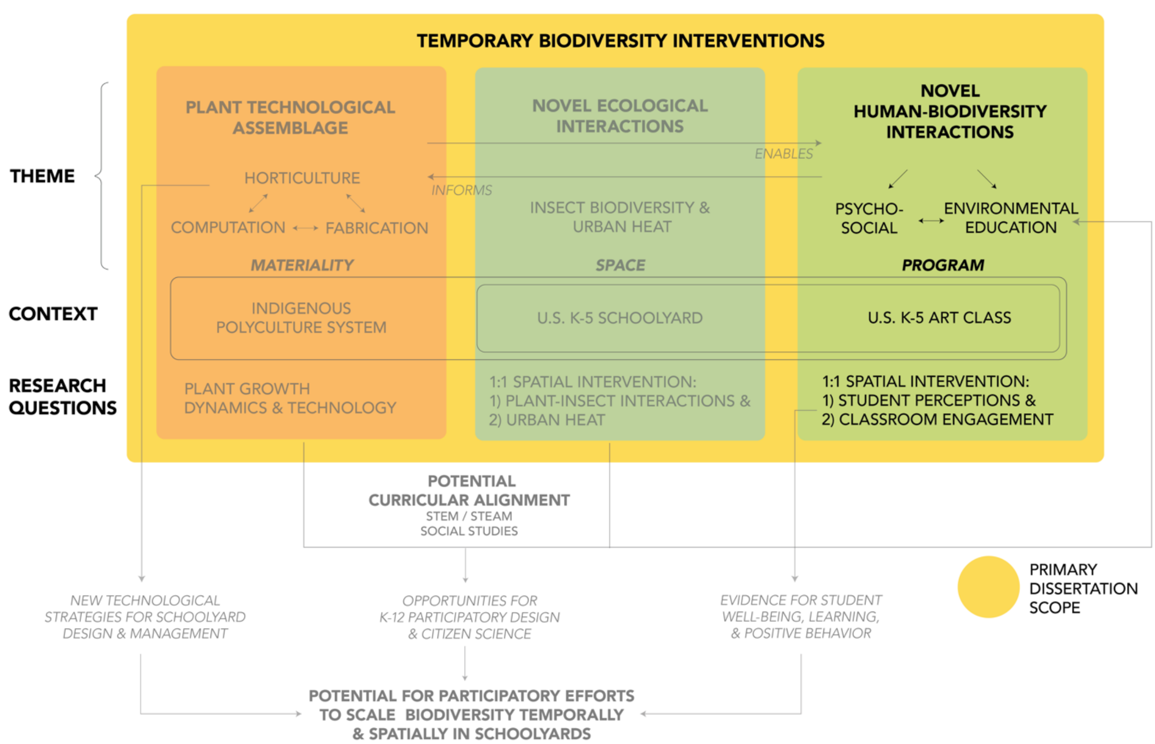


Figure 43: Interdisciplinary framework of dissertation – Human Behavior

Asphalt to Ecosystems: Classroom Engagement and Perceptions of Biophilic Tactical Urbanism in an Elementary Schoolyard", submitted to *Environmental Education Research.*

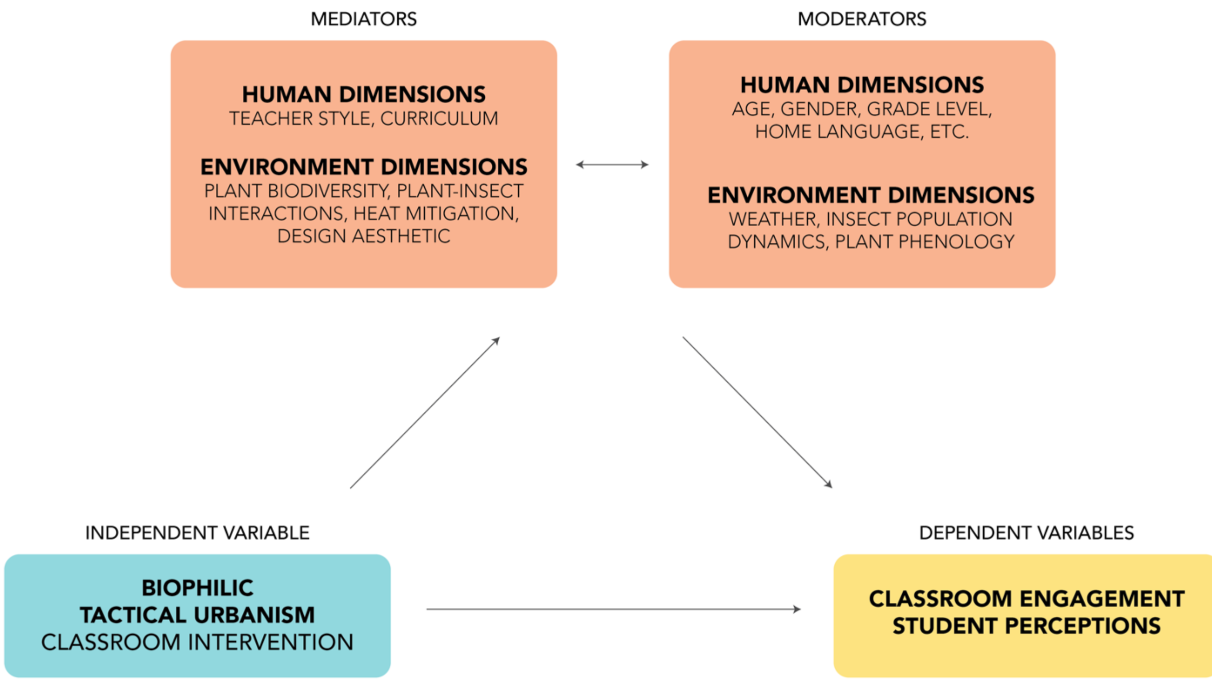


Figure 44: Conceptual model for independent and dependent variables, and mediators/moderators, including those related to earlier chapters (ecology and technological assemblage). Note that this list is not exhaustive, nor did the dissertation investigate every mediators/moderator listed.

6.2 Abstract

This paper extends research on the greening of schoolyards and its benefits for child development through the process of tactical/temporary urbanism (T/t urbanism)–temporary, low-cost interventions that seek to shift public spaces towards more sustainable futures. A "pop-up biophilic" classroom was deployed in an elementary school parking lot in the mid-Atlantic U.S and effects on student engagement and perceptions of biodiversity were investigated. Through a mixed-method, co-design framework, an art teacher taught students in the temporary outdoor classroom. Researchers hypothesized that this space would improve student engagement

compared to a conventional indoor classroom. Engagement was measured via student attention redirects, teacher evaluations, and classroom outputs for 4^{th} and 5^{th} graders (n=115), and showed improvement over a period of three weeks. Additional research investigated student perceptions of biodiversity in the pop-up classroom through nature photography with 4^{th} and 5^{th} grade students and developmentally across 1^{st}, 3^{rd}, and 5^{th} grade levels (n=201). Photographs were analyzed for student perceptions of biodiversity in the temporary environment. Collectively, this research demonstrated the potential for temporary, nature-based classrooms to improve student engagement and measure perceptions of biodiversity, while testing novel curriculum-engaged spatial methods in environment-student interaction.

6.3 Introduction

Regular educational experiences in nature have been shown to promote student learning and broader development by providing educational, mental, social, and physical benefits (Kuo et al., 2019; Mann et al., 2022), support developmental of environmental literacy (Ardoin & Bowers, 2020), and childhood experiences like these may play a key role in fostering pro-environmental values and connectedness to nature later in life (Chawla & Derr, 2012; Cheng & Monroe, 2012; Evans et al., 2018; Rosa et al., 2018). Collectively these personal attributes are likely important for promoting environmental education objectives in support of many of the 17 UN Sustainable Development Goals and 169 sub-targets (*UNESCO Global Action Programme on Education for Sustainable Development*, 2016). How to incorporate nature-based experiences such as green schoolyards to maximize student benefit in the complex, resource-limited context of K-12 public schools in the U.S. and beyond is an on-going challenge for many school districts (Stevenson et al., 2020). For example, what kind of nature-based spaces, how often could/should educators use them and in what contexts, and most importantly how do researchers translate and scale this knowledge–answers to these questions could inform educational policy and the design of learning environments. The present study considers these questions through the lens of student classroom engagement and perceptions of nature with photography using a temporary nature-based classroom intervention as a novel methodological tool.

Student Engagement in Classrooms with Nature-Based Elements

Classroom engagement is defined for this research study as a "student's ability to pay attention and stay on task in class" (Miller et al., 2021). Lack of student engagement is considered one of the biggest challenges that teachers face in the classroom (Parsons & Taylor, 2011). Student classroom engagement benefits from learning environments that incorporate nature compared to conventional classrooms and typical learning environments, at diverse spatial and temporal scales, and intensities of nature. At one extreme, forest schools and related pedagogical models where nature is deeply integrated into curriculum and spatial design provide a range of benefits including classroom engagement (Harris, 2024; L. O'Brien & Murray, 2007; Roe & Aspinall, 2011). In more conventional schools settings, research has shown that students are more engaged in outdoor classroom settings compared to indoor classrooms (Francis Norwood et al., 2021; Guardino et al., 2019; Kuo et al., 2018; Largo-Wight et al., 2018), are more attentive in indoor classrooms with green walls (van den Berg et al., 2017), and have better attention and lower stress in indoor classrooms that have windows with green viewsheds (Li & Sullivan, 2016).

Psychological mechanisms driving this increased student engagement draw from two theories of mental restoration: Attention Restoration Theory (Kaplan, 1995) and Stress

Reduction Theory (Ulrich et al., 1991). Attention Restoration Theory posits that nature exposure restores depleted attention resources through cognitive processes, while Stress Reduction Theory operates through a different pathway, whereby nature exposure improves affect and lowers underlying physiological stress. Collectively, increased attention capacity and lowered stress levels due to nature exposure are theorized to support greater classroom engagement (Mason et al., 2022). For example, vegetated, nature-based learning environments may provide a calmer, quieter space than normal indoor classrooms, which can lower student stress and promote greater engagement (Kuo et al., 2019).

Concomitantly with these psychological health benefits, the novel and dynamic setting of outdoor learning environments provide loose materials and unique educational affordances for student self-direction, curiosity, and awe, which can all promote classroom engagement and learning more broadly, while also supporting the above mental health benefits (Williams et al., 2018). Problem-based learning and place-based learning, both of which are associated with greater student engagement and positive learning outcomes, are also accessible in nature-based outdoor learning environments (Miller et al., 2021). Finally, the extra instructional space of outdoor learning environments and associated physical movement of students to an outside location provides an outlet for physical activity, which could improve student engagement and self-regulation (Kuo et al., 2018).

Student Perceptions of Biodiversity in Classrooms with Nature-based Elements

Along with classroom engagement, how students perceive classrooms with nature-based elements – in this case biodiversity – could provide an important perspective on the formation of important personal attributes for UN Sustainable Development Goals such as environmental literacy, connectedness to nature, and pro-environmental values. From a broader perspective, the direct human experience of biodiversity appears to be declining globally in many cultures, described as an extinction of experience (Soga & Gaston, 2016), including in children (Louv, 2008b; Soga et al., 2020). This could result in greater apathy towards biodiversity concerns and at worst a biophobia feedback loop that reinforces negative perceptions of biodiversity (Soga et al., 2023), with long term negative consequences for conservation efforts. Childhood and learning environments provide a unique developmental period and context to understand and influence these perceptions. For example, perceptions of biodiversity are fluid in children and can be improved through environmental education efforts (Lindemann-Matthies, 2002).

Perception of biodiversity is a complex construct that involves both sensory information and subjective experience (Farris et al., 2024). Literature supports the notion that people often perceive biodiversity poorly compared with the actual biodiversity present, including plants (Breitschopf & Bråthen, 2023), insects (J. S. Wilson et al., 2016), and in gardens with birds and pollinators (Shwartz et al., 2014). Moreover, a growing body of research suggests that the perceived level of biodiversity (compared to actual biodiversity) may be a stronger predictor of well-being (Dallimer et al., 2012; Gonçalves et al., 2021; Nghiem et al., 2021; Rozario et al., 2024; Schebella et al., 2019) and connectedness to nature (Southon et al., 2018). In other words, perceived biodiversity is a practical indicator for how people think about and experience biodiversity, with implications for psychology and environmental education.

In children and environmental education specifically, visual perceptions of biodiversity have often been explored through analysis of their drawings (Howlett & Turner, 2023; Montgomery et al., 2024; Morón-Monge et al., 2021). The use of nature photography as an alternative method for capturing student perceptions of biodiversity (and nature writ large) has been underexplored and is considered in this paper. Extending beyond biodiversity, participatory photography-based instructional methods have shown promise as an effective teaching tool in environmental education contexts (Derr & Simons, 2020), with photos providing a unique window into the "interest, curiosity, and engagement of students...critical intermediary outcomes in environmental education programs and initiatives" (Ardoin et al., 2014). One related research study with 6th graders and photography found that connectedness to nature correlated with a greater diversity of photographed phenomenon and geographies (Bezeljak Cerv et al., 2024). Given the opportunity to photograph across built and natural environments, students allocated most photos (70.4%) to vegetation (e.g. trees, forests, flowers, and meadows) compared to the built environment. From the social sciences, photovoice methods which incorporate written/spoken descriptions with photographs, illuminate a deeper, qualitative understanding of child perspectives (Wang & Burris, 1997), including in children (Abma & Schrijver, 2020; A. J. Nguyen et al., 2024).

Participatory nature photography with photovoice-related methods could be used to explore how children perceive different taxa of biodiversity such as plants, mammals, birds, and insects. Insects in particular provide a compelling biodiversity subject as they are critical for many food webs and ecosystem services including pollination (Potts et al., 2010) and are declining globally (van Klink et al., 2020). From an environmental education frame, they are ubiquitous and relatively easy to photograph yet are not often incorporated into K-5 environmental education curricula (Sitar et al., 2023). Early childhood and elementary school education years represent a critical period for developing environmental literacy (Ardoin & Bowers, 2020), yet there are certainly developmental differences between this broad range of ages (0-11). Understanding how perceptions of insects change during the period of elementary education (age 5-11) could provide useful insight for environmental education programs but has not been explored to the knowledge of the authors.

Perception of insects is complex, eliciting a range of possible emotions from positive (e.g. butterflies) to negative (e.g. wasps) (Kellert, 1993; Lockwood, 2013)–a potentially unique indicator for perceptions of biodiversity. From an affective perspective, negative attitudes towards "bugs" appear to be increasing due to urbanization (Fukano & Soga, 2021). At the same time, regular engagement with insects such as gardening increases positive emotions towards them (Vanderstock et al., 2022), while positive emotional experiences with insects is associated with greater connectedness to nature in citizen science (Butler et al., 2024). The connection between perception and affective state in the context of biodiversity (including insects) has not been deeply explored (Brick et al., 2023), but research suggests that affective state (e.g. joy, fear) can mediate how we perceive our environments and vice versa (Zadra & Clore, 2011). Photovoice-oriented photography could theoretically help untangle how perceptions of biodiversity develop (insects and beyond) in children and how these perceptions relate to affect.

State of U.S. School Outdoor Learning Environments

The current study utilized a novel outdoor biodiversity intervention to further elucidate relationships between schoolyard greening, student engagement, and perceptions of biodiversity. First, spatial strategies such as schoolyard greening, the construction of outdoor classrooms, and associated curricular alignment have emerged as common goals in the United States (Jordan & Chawla, 2019) and beyond. At the same time, there remain significant gaps between ideals and practice. Many U.S. schoolyards still consist primarily of turf, pavement, and other safety-oriented surfaces, largely devoid of ecological richness and associated educational affordances

(Barnes & Barnes, Audrey, 2023; Schulman & Peters, 2008). The reasons for this are myriad. Improvements to outdoor learning environments require significant financial and physical resources which many school districts may lack, both for installation and ongoing maintenance (Stevenson et al., 2020). School administrators and teachers may be risk averse to outdoor learning due to liability concerns (Oberle et al., 2021). Teachers especially may have low motivation and/or negative attitudes about the benefits and/or ease of outdoor learning (Bilton, 2020). Even when outdoor learning environments are present, educators may face environmental barriers for outdoor, nature-based learning including travel time and poor weather (Ernst, 2014; van Dijk-Wesselius et al., 2020).

Using Biophilic Tactical Urbanism to Explore Research Questions & Reimagine Schoolyards

To creatively explore some of the challenges to outdoor, nature-based learning in public schools listed above and provide a platform for research on student engagement and perceptions of biodiversity, the current study employed a temporary, nature-based outdoor classroom installation. A pop-up, biodiversity-centered classroom was designed, built, and deployed in a public K-5 elementary schoolyard parking lot in Virginia, U.S in a co-design partnership (Sanders & Stappers, 2008) with a schoolteacher. This intervention built on the concept of *tactical/temporary urbanism* – short-term, low-cost interventions in public space intended to spark positive, longer-term changes in the built environment (Lydon & Garcia, 2015; Fig. 41). Tactical urbanism, also known as temporary urbanism (Bishop & Williams, 2012) and bottom-up urbanism (Stevens & Dovey, 2022), has emerged as a common design and planning tool across cities globally, particularly for street and pavement re-designs. For example, the shift of Times Square in New York City from automobile-centric to pedestrian-centric began with tactical urbanism interventions featuring furniture and street vendors (Lydon & Garcia, 2015). Tactical urbanism as a community sustainability redesign tool directly aligns with UN Sustainable Development Goal 11 - Sustainable cities and communities (*United Nations: Transforming Our World - the 2030 Agenda for Sustainable Development*, 2015).

Figure 45: Examples of tactical/temporary urbanism

The pop-up classroom incorporated ecologically designed components, particularly plant biodiversity, that drew from biophilic design principles (Kellert et al., 2011) and were aligned with K-5 curriculum goals in science and social studies (Fig. 42). This approach was termed *Biophilic Tactical Urbanism* (BTU). Additionally, the temporary plant installations acted as habitat for a range of insects and other terrestrial arthropods like spiders (described collectively as “insects” from here forth). The BTU installation served as an outdoor learning space that was functional, accessible, low-cost (<$5000), and publicly demonstrative – in the spirit of T/t urbanism. The architectural intervention also provided a unique learning environment to explore empirical nature-child interaction research questions where temporal and spatial attributes of a learning environment could be manipulated for empirical research. A literature review identified no peer-reviewed publications that explored the application of T/t urbanism to outdoor learning environments. Nor has there been significant empirical research on the impacts of T/t urbanism in other programmatic contexts outside of education. One of the few existing studies examined the effect of a low-cost tactical urbanism intervention in an urban waterfront setting (Roe et al., 2019). Pedestrian users of the space were shown to have lower stress and perceived stress compared to controls.

Figure 46: Deployed biophilic T/t urbanism classroom for the research study, from above and in-use by students

Research Questions & Teacher Participatory Process

Could the benefits of outdoor, nature-based learning on student engagement be extended to a schoolyard parking lot with pop-up furniture and planters on pavement? What could be learned about student perceptions of biodiversity in this space? The study compared the BTU classroom to a conventional indoor classroom for engagement research questions and partnered with an art teacher specifically to explore perceptions of biodiversity.

Collaboration with the school art teacher represented a strategic curricular partnership for several reasons. First, art teachers typically instruct every student in a K-5 setting, increasing the sample size, while controlling for the effects of different teachers among primary classrooms. Second, art provides a flexible curricular context for human subject research compared to core curricula and can theoretically more easily accommodate novel research interventions, in this case nature photography. Third, from an affective perspective, a sense of connection to nature – one potential driver for the student engagement benefits of outdoor, nature-based learning – is thought to be more readily nurtured in an affective context (Cheng & Monroe, 2012; Rosa et al., 2018). Making and appreciating art provides clear opportunities for affective-oriented learning – more so than didactic-oriented subjects such as core curricula in math and grammar. Finally, from an environmental psychology perspective, engaging in art provides opportunities for fascination, intrinsic motivation, reflection, and mind-wandering–all thought to be critical for attention restoration and associated mental health (Basu et al., 2019; Williams et al., 2018). These theoretical ideas are supported through research into nature-based art education (Moula et al., 2022) and art therapy more broadly (McDonald & Drey, 2018) which have shown related mental health benefits.

In partnership with the school art teacher, the researchers co-developed the following research hypotheses on student engagement in a biophilic tactical urbanism (BTU) art classroom compared to a conventional art classroom:

H1: Classroom engagement will be higher in a pop-up BTU classroom compared to a conventional indoor classroom, measured through student attention redirects, teacher evaluations of classroom engagement, and student classroom outputs for 4^{th} and 5^{th} grade students.

H2: Students will prefer instruction in a pop-up BTU classroom compared to a conventional indoor classroom, measured through student polling of 4th and 5th grade students.

To explore student perceptions of biodiversity, the following hypotheses were co-developed:

H3: Among their photographs, 4th and 5th grade students will select favorite photovoice photographs from the BTU intervention that feature biodiversity (plants and insects) and the captions of their favorite photos will explicitly express positive affective language (e.g. joy, happiness, delight, fun, surprise).

H4: Between 1st, 3rd and 5th grade, there will be no differences in how students engage with insects through nature photography based on the percentage of photos featuring insects.

6.4 Methods

Design & Spatial Context

The Biophilic Tactical Urbanism intervention was fabricated during summer 2024. The classroom consisted of wooden armatures (9 in total) for potted plants, each covering ~2.5 m^2 (26 ft^2) for a total area of ~22 m^2 (237 ft^2) and less than $5000. These were designed to be modular, aesthetically compelling, and appropriately scaled for an elementary school student population and informed in part through a participatory co-design process (Sanders & Stappers, 2008) with visioning workshops featuring students and college students at the study school the prior year (Fig. 43).

Figure 47: Co-design of potential outdoor classroom spaces with college and elementary school students

The modular design allowed for different spatial arrangements depending on programmatic needs including a green wall, façade, terrace, and pergola pole. Collectively the BTU system was arranged in the school parking lot to emulate a semi-enclosed outdoor learning environment (Fig. 44), approximately 100 m^2 (1100 ft^2) and compared in size to the conventional art classroom. Hole patterns in the armature platforms provided a canvas for different planting arrangements (Fig. 45). Plants were either annual agriculture species grown over the summer or perennial native wildflowers donated from a local nursery. Approximately 200 plants were incorporated into the installation. These were arranged in a series of planting designs, representing different ecosystem vignettes, spatial affordances, and educational opportunities. Ecosystem vignettes including 1) native pollinator meadow, 2) indigenous agriculture ("the Three Sisters"), 3) monoculture (corn), 3) shade pergola ("September-pole"), and 4) STEM (plant behavior).

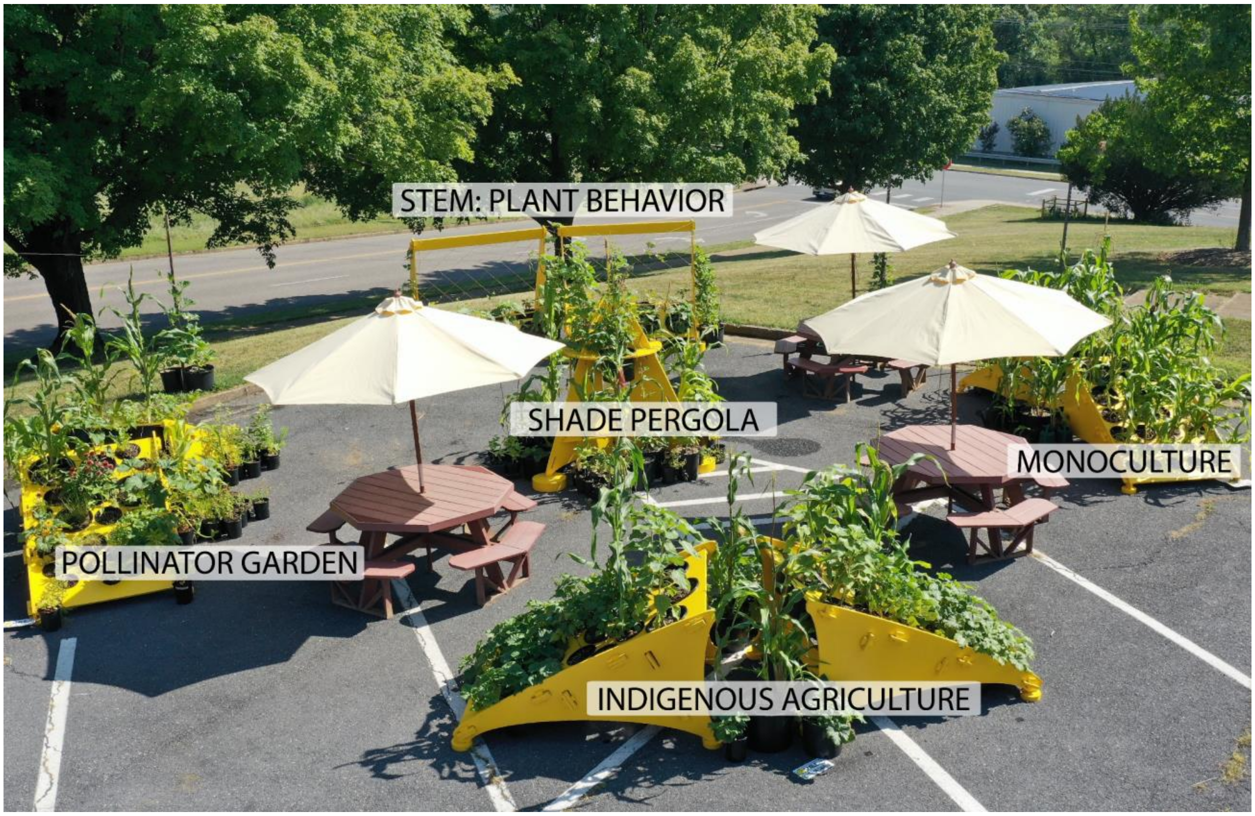


Figure 48: BTU classroom ecological vignettes

The BTU classroom was deployed August-October 2024 at Keister Elementary School, a title 1 (low median socio-economic status) school in Harrisonburg, Virginia. The location was a parking lot adjacent to the school building with convenient access for students and teachers (Fig. 46).

Figure 49: Design, transport, assembly, and deployed stages for the BTU system

Figure 50: Location of BTU installation and site prior to deployment

Participant Characteristics

The human subject design of the study fell under “normal educational practice” which aided subject recruitment because written guardian approval was not required for participation, thus increasing the likely sample size. This was particularly important for the title 1 school (50% of families are below the poverty line) since the student body contained a broad range of socio-economic statuses, cultural backgrounds, and home languages (>30 for the school), including a significant immigrant population. At the school, the ethnic makeup was 47% Hispanic/Latino, 38% White, 9% Black, 4% mixed ethnicity, and 2% Asian. 37% were considered active English learners. Collectively these factors could have produced selection bias if written guardian approval was required. However, it did influence the study design since only psycho-social instruments that were considered part of normal educational practice could be utilized. Student datasets for each child were anonymized. Ethical approval for the study was provided by University of Virginia’s Social and Behavioral Sciences Institutional Review Board (SBS IRB).

For hypotheses 1-3, participants were recruited from four 4th grade classes (age 9-10) and four 5th grade (age 10-11) classes of students (n=115, mean class size 14.75). For hypothesis 4 which explored developmental differences in nature-based photography, participants who were recruited from the same 5th grade students were compared against four 3rd grade classes of students (n=61), and four 1st grade classes of students (n=73). Recruited 1st (age 5-6) and 3rd grade (age 8-9) classes did not participate in hypotheses 1-3. Guardians were allowed to opt out their children from the study, but none did. Notably, the same art teacher instructed every student, which controlled for teacher effects.

Study Design

Students were instructed in a nature photography art lesson plan for three class periods over three weeks during their regular art period (one 50-minute class period per week; Fig. 47).

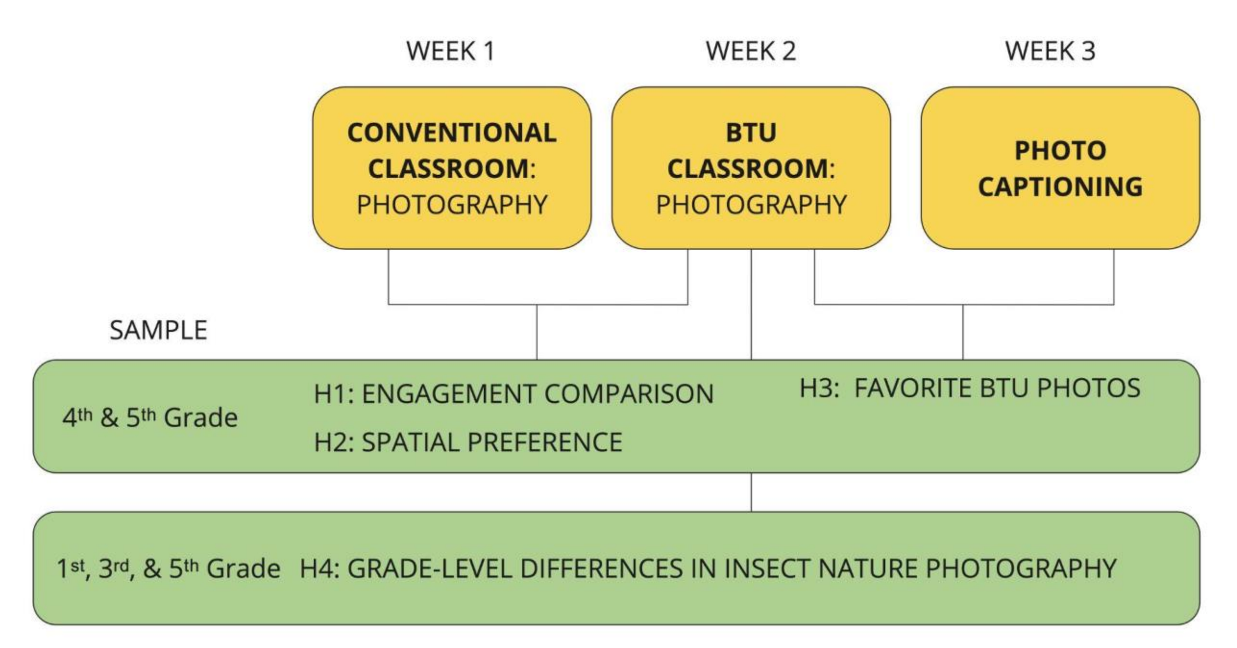


Figure 51: Study design, sample grade levels, and associated hypotheses

Each student was provided a Kodak PixPro WPZ2 digital camera for nature photography. During week 1 the art teacher provided basic instruction on camera usage in the conventional indoor art classroom setting, along with tips on nature photography. Students were then instructed to engage in self-directed nature photography in the indoor classroom for 30 minutes. Nature-oriented materials including posters and potted plants were displayed in the space to provide potential nature photography objects of interest (Fig. 48). Students were discouraged from photographing each other. Any photographs featuring identifying human subject information were screened by the teacher and deleted.

Figure 52: Conventional art classroom

Week 2 occurred in the BTU outdoor classroom, with the 30-minute photography activity from week 1 directly paralleled (Fig. 49). Students were instructed to only work in the defined perimeter of the BTU classroom. Instruction in the space only occurred on fair weather days with no precipitation and ambient temperatures below 29° C (84° F). During the study period, weather met these conditions during every class period and no BTU class periods had to be rescheduled.

Outcome Measures

A table of all measures and associated hypotheses is presented in Table 3.

	Hypothesis	Measures
H1	Classroom engagement differences between conventional & BTU classroom	Teacher redirects / Teacher evaluation of classroom / # of student photographs
H2	Classroom preference differences between conventional & BTU classroom	Student polling
H3	Favorite photography in BTU classroom & associated affect of caption	Favorite photo / Associated caption / Image content analysis
H4	Grade-level differences in nature photography in BTU classroom	Number of photos and image content analysis

Table 3: Outcome measures for each hypothesis

In both indoor and BTU settings, behavioral data on student engagement were measured. This included 1) teacher redirects, 2) teacher evaluations of classroom engagement, and 3) student outputs. Teacher redirects were measured anytime the teacher redirected a student's attention during class (e.g. "Pay attention") in either the instructional or activity part of the class time and tallied at the classroom level. The teacher's evaluation of classroom engagement was assessed on a scale of 1-5 at the end of each class, with 1=very low classroom engagement, and 5= very high classroom engagement, and based on an existing assessment tool (Kuo et al., 2018).

Additionally, the number of photos taken were tallied as a metric of student engagement in the class. Finally in the third week, students were informally polled for their classroom preference (conventional indoor vs BTU classroom) via secret ballot (hand raising). In week 3, 4th and 5th grade students reviewed their BTU nature photographs on iPads and selected their single most favorite photograph. This photo was printed, and students wrote a caption about the photo from the prompt “Tell us a story of the photograph / What do you want the viewers to know about it?” Photos were coded for whether the subject of the image contained plants, insects, plants and insects, the built environment, sky, art artifacts (trinkets provided by the teacher), or a combination of each. Responses were coded for the presence of affective expressions (e.g. such as “I felt”, “I love”, “It made me scared”). For hypothesis 4 which explored developmental differences between grade levels, 1st and 3rd graders participated in an identical study design as 4th and 5th grade students, but only photographic artifacts were collected. Photos were analyzed for the presence of insects as a potential indicator for how different developmental stages affect perceptions of insects.

Figure 53: Student photographing a bee on a sunflower; the BTU classroom in use by a group of students

Data Analysis

All statistical analyses were performed in SPSS and included a Wilcoxon signed-rank test for H1, Chi-Square Goodness-of-fit for H2 and H3, and one-way ANOVA with post-hoc Tukey test for H4.

6.5 Results

Classroom Engagement Differences between BTU & Conventional Classroom

Summary results for H1 and H2 are presented in Table 4. For **H1** (Classroom engagement will be higher in a pop-up BTU classroom compared to a conventional indoor classroom), results are described individually for student attention redirects, teacher evaluations of classroom engagement, and student classroom outputs for 4th and 5th grade students.

	H1: Classroom engagement differences between conventional & BTU classroom (mean values)			H2: Classroom preference differences between conventional & BTU classroom
	Number of teacher redirects	Teacher evaluation of classroom engagement (1-5)	# of student photographs	Number of students
Conventional classroom	15.5	3.9	24.1*	5*
BTU classroom	9.4	4.6	33.7*	110*

Table 4: Summary of Student engagement and classroom preference differences between conventional and BTU classrooms (* p<.001))

Examining classroom-level student redirects and teacher evaluations of classroom engagement, Shapiro–Wilks and Kolmogorov–Smirnov tests of normality revealed the data was not normally distributed and the small sample size (n=8) did not allow for statistical analysis. The mean number of student attention redirects per classroom was 15.5 per instructional period (median=15.5) in the conventional classroom, and 9.4 (median=9.5) times in the BTU classroom, a difference of 6.1 redirects per instructional period (Fig. 50).

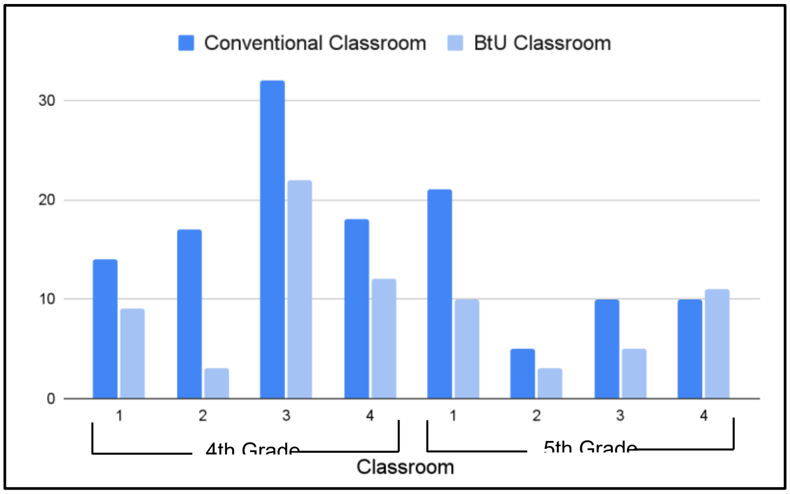


Figure 54: Classroom-level student redirects in conventional and BTU classroom

The teacher evaluation of classroom level engagement, measured on a scale of 1-5 found equal or greater levels of engagement in the BTU classroom compared to the conventional classroom (Fig. 51) with a mean of 3.9 in the conventional classroom and 4.6 in the BTU classroom.

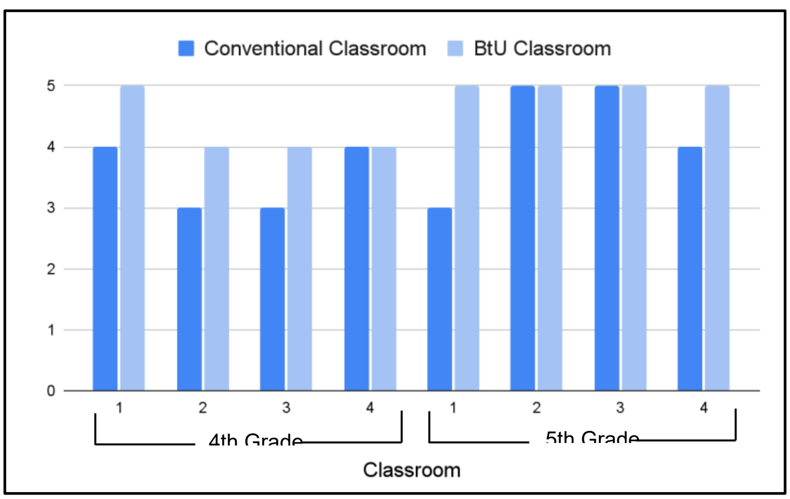


Figure 55: Teacher evaluation of classroom level engagement (1-5 scale, 5=high) in conventional and BTU classroom

Examining student outputs as a proxy for classroom engagement, the number of photographs taken by each student in each environment were compared. Shapiro–Wilks and Kolmogorov–Smirnov tests of normality revealed this data was not normally distributed, and a Wilcoxon signed-rank test was performed for the paired data. For this student level measurement, the test revealed a significantly greater number of photos taken in the BTU classroom ($M=33.7$; median 28.0) compared to the conventional classroom ($M=24.1$; median 22.0) and supported the hypothesis that classroom engagement would be higher in the BTU space ($z=5.27$; $p<0.001$).

For **H2** (Students will prefer instruction in a pop-up BTU classroom compared to a conventional indoor classroom, measured through student polling of 4th and 5th grade students.), found that 110 of 115 students preferred instruction in the outdoor BTU classroom compared to the indoor conventional classroom via blind hand raising. Five students preferred instruction in the conventional classroom. A Chi-Square Goodness-of-fit test found that there was a statistical difference in preferred classroom space ($\chi^2=98.78$; $df=1$; $p<.001$).

Student Perceptions of Biodiversity in the BTU Classroom

Results for H3 (Among their photographs, students will select favorite photovoice photographs from the BTU intervention that feature biodiversity [plants and insects] and the captions of their favorite photos will explicitly express affective language) are shown in Fig. 52 and along with representative student photographs (Fig. 53). A Chi-Square Goodness-of-fit test found that there was a statistical difference between the types of content in selected favorite photographs (χ^2=139.00; df=6; p<.001). The majority of photos featured some form of nature (82), either plants (57), insects and plants (24), insects (1), or art artifacts with plants (19).

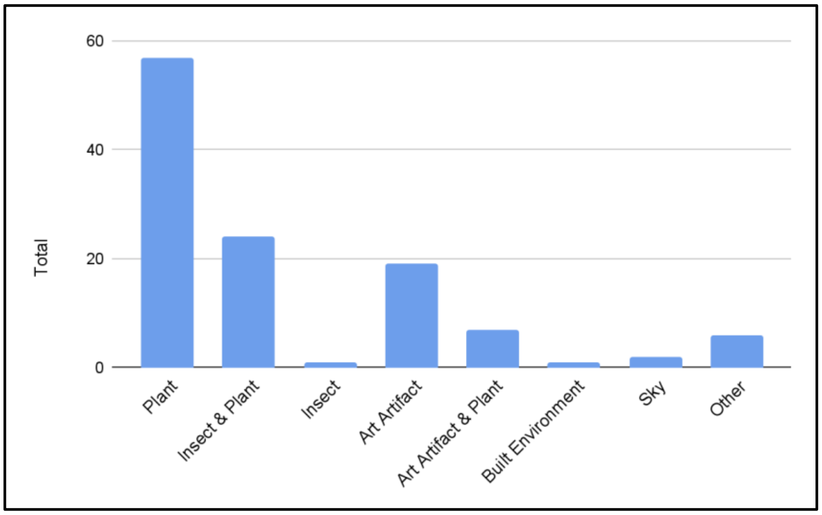


Figure 56: Distribution of favorite photograph image content

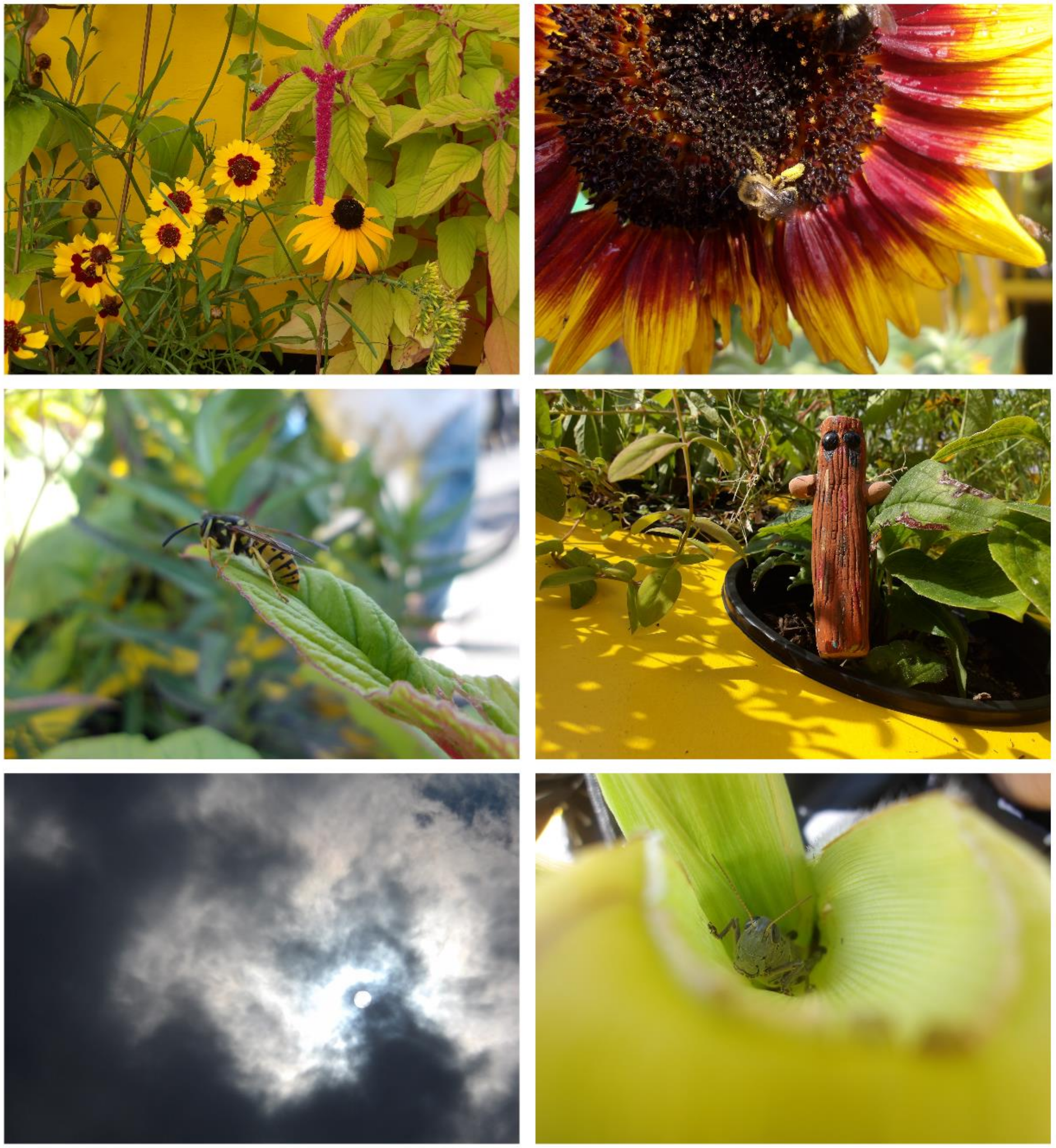


Figure 57: Example favorite photos selected by 4th and 5th grade students: insects, plants, and art artifacts

Of the 63 photos that included nature (plants, insects, or insects and plants), narrative coding of image captions revealed 21 expressed affective written language in their descriptions, with the remaining 42 providing descriptions without affective language. 19 of the 21 contained positive affective valence in their writing, while 2 contained a mix of positive and negative affective valence, specifically around their fear of bee stings. Examples of affective and non-affective captions are below:

Affective captions:

> “Nature is beautiful, you have to explore it and find what you like. I love the photo so much”
>
> “This was scary because I don't like bees but they were very nice!”
>
> “So when I was taking pictures I felt calm, but when I took that picture I was feeling a bunch of emotions because there was a big bumble bee right in front of me. I wanted to run and scream cause I was scared but I knew that if I did all of that I would get stung:

Non-Affective captions:

> “I was walking around and saw it and took a picture.”
>
> “This photo shows the seeds of a sunflower close up and you can see the texture very clearly. It reminds me of a farm – the different colors of green and purple.”
>
> “I decided to choose this photo because I thought it looked like a different plant.”

Based on this qualitative data, H3 is partially supported. Students did tend to photograph elements of biodiversity, though the majority of these narrative captions did not include affective language.

Regarding **H4** (Between 1st, 3rd and 5th grade, there will be no differences in how students engage with insects through nature photography based on the percentage of photos featuring insects, found there was statistically significant differences as determined by a one-way ANOVA ($F(2,198) = 15.2$, $p = <.001$). Post hoc comparisons using the Tukey HSD test indicated that the mean percentage of photos featuring insects for 1st graders ($M = .08$, $SD = .09$) was significantly lower than the 5th graders (M = 0.20, SD = 0.13). However, the 3rd graders (M =0.14, SD = 0.15) did not significantly differ from the other grades. This hypothesis was rejected based on the data and results are presented in Fig. 54.

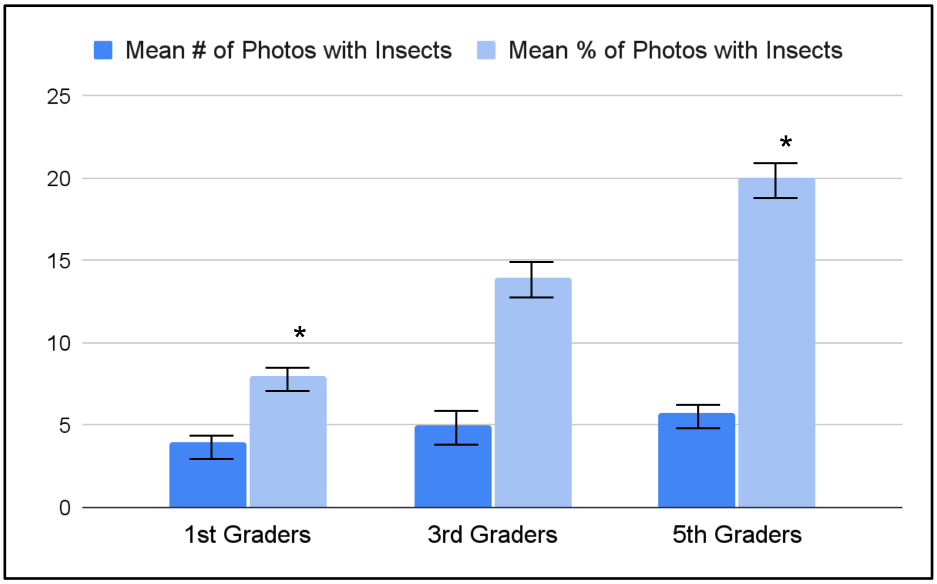


Figure 58: ANOVA results comparing grade level and photographs featuring insects
* Post hoc Tukey statistical differences at 0.05 level

6.6 Discussion

Classroom Engagement & Preference differences between BTU & Conventional Classroom

Results supported **H1** and **H2**; student engagement was higher in the BTU classroom and students preferred this classroom space over the conventional classroom. Teacher redirects of student attention and teacher evaluation of classroom level engagement were each higher in the pop-up classroom compared to the conventional classroom–though the limited sample size (8 classrooms) did preclude statistical analysis. However, these results track with previous studies on student engagement in outdoor classrooms (Francis Norwood et al., 2021; Guardino et al., 2019; Kuo et al., 2018; Largo-Wight et al., 2018). These studies occurred in permanent outdoor classrooms with abundant, permanent greenery while the current research extends these effects to a barren parking lot with a temporary garden setting. Students also took more photos in the BTU space as well–a potential proxy for classroom engagement.

For each engagement measure, it could be argued that the novelty of the environment played an outsized role in classroom engagement; the BTU space represented a new, ecologically dynamic context for all students and that may have driven more interest in photography and attentiveness in class. Another study design could have compared the conventional classroom to an existing outdoor classroom space. While this cannot be ruled out, typical outdoor, nature-based settings are often dynamic spaces, providing often unpredictable interactions with nature. In other words, the novelty of the BTU space was thought to conceptually mimic the ever-changing context (and benefits) of outdoor, nature-based learning where classrooms may not be spatially or ecologically fixed. Indeed, "newness in outdoor classrooms" may itself drive classroom engagement (North et al., 2023) and supports the potential of T/t urbanism as a unique strategy for educators to "change it up."

Notably, the number of photos taken was aggregated at the student level among different classrooms, and teacher redirects were aggregated at the classroom level. Both measures aggregated two grade levels, rather than being analyzed through a multi-level model. This decision stemmed from the small cluster size which limited statistical power (8 classrooms), as well as aspects of the study design that were thought to minimize potential between-classroom differences: the incorporation of paired measurements for each student for photos taken and the same teacher teaching every classroom. A future study could explore potential classroom-level effects through a larger sample size featuring multilevel modeling. Another concern for the study is there may be order effects since the spatial interventions went indoor conventional classroom condition, followed by outdoor BTU classroom condition for all subjects. This study design decision emerged because the teacher had significant concerns about training students on the digital cameras (which were novel for all participants) in a new outdoor setting, especially early in the school year. The tradeoff likely produced increased student competency with the technology and photography techniques but may have introduced practice effects that impacted the results. This tension between “real-world educational application” and “empirical design” was an emergent theme of the study.

More broadly, a stronger experimental design might have included as a third condition the school parking lot without the BTU intervention. Would the impacts on student engagement have been as significant in the parking lot without temporary nature? Perhaps simply being outside, or the physical process of walking to a different classroom space, drove some of the impacts on student engagement. The researchers decided to exclude an empty parking lot condition due to resource constraints and because of the art teacher’s concerns that it would be an unethical, artificial, and ineffective teaching environment; nature photography in an empty parking lot would likely never occur in real world situations.

H3: Perceptions of Biodiversity via Favorite Photographs and Associated Captions

The application of participatory nature photography in the BTU classroom setting represented a novel and exploratory line of research. **H3** (Among their photographs, students will select favorite narrative photographs from the BTU intervention that feature biodiversity [plants and insects] and the captions of their favorite photos will explicitly express affective language), was partially supported. Most students did select favorite photos that featured biodiversity rather than photos of the built environment, sky, or other students (only anonymized photos of students were available for selection). Their captions, however, did not typically contain affective language. Interestingly, art artifacts were another photographic subject of interest. These artifacts were typically small animal figurines provided by the art teacher to engage students in photography. The associated captions were typically very character-driven narratives, suggesting that for some students the ability to generate stories about their nature experiences could be an important method for shaping how they perceive nature and biodiversity through photography.

H4: Age Developmental Differences in Nature Photography of Insects

H4 was rejected (between 1st, 3rd and 5th grade, there will be no differences in how students engage with insects through nature photography based on the percentage of photos featuring insects). 5th grade students were statistically more likely to photograph insects on a percentage basis, compared to 1st grade students. Moreover, the mean number increased directionally in age when 3rd grade students were included. This suggests that as children age from 1st to 5th grade, their interest in insect photography increases, or perhaps they have greater maturity and skill at nature photography.

Future Nature Photography Studies

Overall, participatory nature-based photography provided a compelling tool for researching student perceptions of biodiversity. It was particularly suited to the demographic and language diversity of the student participants at this school since photography does not require English fluency. Moreover, participatory nature-based photography is a unique bridge between a research tool and an education tool. For example, the simple act of taking photos has been shown to produce greater enjoyment of experiences (Diehl et al., 2016). The potential for nature photography to not just measure/document biodiversity but shift perceptions, affect, and/or attitudes should be explored in the future. Additionally, deeper investigations of child perceptions of insects through photography in a more directed manner with measures such as connectedness to nature to better understand perceptions and attitudes about insects are recommended.

BTU as Novel Environment-Child Research Tool

Biophilic Tactical Urbanism offers many affordances for exploring environmental education questions with children and beyond. Researchers were able to design and control the location and layout of a classroom space including the selection of vegetation, bloom time, etc. Moreover, all of this occurred with limited resistance from school administrators since no permanent modifications were needed to school infrastructure. The partner school was indeed welcoming of the temporary installation as it filled a need for outdoor classroom space. As a challenge, fabrication of the armatures represented a significant investment of time. Future research studies or applications could engage middle or high school students in the fabrication process, providing a pathway for both BTU scalability and hands-on learning in architectural and engineering processes for students.

Future BTU Research Studies

The study occurred early in the academic school year which coincided with the plant growing season in the geographic region. It would not have been practical over colder, winter months; BTU learning environments like this may be best suited as a fair weather, seasonal strategy for temperate climates. That being said, future research could explore how BTU could be designed for different seasonal and climatic conditions such as winter and spring months when outdoor learning is more physically challenging but represent a large portion of instructional days for many regions, especially the global north. Furthermore, the current study only included herbaceous perennials and annuals as part of the planting design. Though larger, in-ground trees were adjacent to the site, they were not part of the defined classroom space. A future study could compare how the BTU environment compares to a permanent outdoor learning environment with more established vegetation like trees, which are positively associated with student performance and cognition (Dadvand et al., 2015; Kuo et al., 2021)

Finally, the study can only comment on the impact of BTU in art education which might be a unique curricular context compared to core curricula like math and reading. It remains unclear how generalizable the results would be to other subject areas. That being stated, the benefits of nature-based art education, whether in a BTU classroom or not, could provide downstream benefits to children's classroom engagement later in the instructional day and should be explored in a future study. This is theoretically supported by environmental psychology research on school children, where green breaks provide later benefit to student cognition through attention restoration and stress reduction (Amicone et al., 2018; Lee et al., 2015; Li & Sullivan, 2016). Equally, the study measured student engagement at only two time points for short windows of time (50 min/week) during weekly art class. A longitudinal design could provide deeper insight into the durability and dose response curve for student engagement (and biodiversity perceptions) in BTU classrooms.

6.7 Conclusion

This study examined the effect of temporary “pop-up” nature-based installations on student classroom engagement and perceptions of biodiversity through photography. The human subjects research questions emerged through a co-design research framework with a school art teacher. Results found that students were more engaged in the BTU classroom and preferred that space compared to a conventional classroom. Regarding perceptions of biodiversity and associated affective captioning in the BTU space, students selected photographs that featured biodiversity as their favorites (plant and insects), but their photo captions did not necessarily contain affective language. Among three grade levels, students in the oldest grade level were most likely to photograph insects. Along with these empirical results, the research tested an intermediary, applied strategy for schoolyard greening. The methods and outcomes are a proof of this concept – a marker on a road map for future Biophilic Tactical Urbanism research studies and applied strategies that are larger scale, more robust, and lead to permanent shifts in outdoor learning environment design.

Chapter 7: Conclusion

7.1 Summary of Key Findings

This body of research explored novel methods for investigating human-environment interactions through temporary biodiversity interventions: biophilic tactical urbanism (BTU). These interdisciplinary, scaffolded investigations increased in scale and complexity from 1) basic technological research on the assemblage, performance, and aesthetic of plant-based armatures in architectural contexts, to 2) the ecological impacts of a temporary biodiversity intervention on insects and heat and culminating in 3) behavioral responses of children to this intervention positioned as a temporary, outdoor learning environment.

First, Chapter 4 [Technology] explored horticultural growth experiments using a model plant ecology (the Three Sisters) and demonstrated species-specific responses to abstracted architectural scenarios using parametric analysis tools. These investigations tested the phenotypic potential of each plant species, while simultaneously developing novel design research methodologies on plant performance and aesthetics. Collectively, this chapter supports the notion that each species has its own, unique range of morphological potentials to plant training. For example, plant tolerance to bending from abstracted architectural elements such as arches differed dramatically among corn (*Zea Mays*) and sunflower (*Helianthus annuus*). Equally, plant growth and productivity were greater in common beans (*Phaseolus vulgaris*) when plant training was incorporated. These plant growth models and associated digital-physical methods provide a starting point for deeper investigations that 1) directly relate to the dissertation's focus on temporary plant installations, 2) inform research and application on the interactions between plants and the building envelope/built environment more broadly. The latter is an emerging research space (Weisser et al., 2023) with limited peer-reviewed literature (Barnes & Barnes, 2022).

Second, Chapter 5 [Ecology] examined the impacts of BTU on ecological systems that were designed, fabricated, and grown based on research from Chapter 4 [Technology]. Insects from the surrounding environment utilized the BTU planting armatures and the diversity of insect families increased with increased plant richness. This was statistically significant between low biodiversity and high biodiversity planting design–6.5 to 11.6 insect families respectively. Bees, wasps, and other pollinating Hymenoptera were by far the most common family of insects measured, likely driven by the availability of floral resources in the planting designs. These findings track with related studies on the relationship between plant diversity and insect diversity in fragmented natural habitats (Tscharntke & Brandl, 2004) but extend this to temporary contexts. Additionally, BTU armatures were found to significantly reduce parking lot surface temperatures. On a summer day with an ambient temperature of 34°C (93°F), the exposed pavement surface temperature reached 62°C (143°F), mean pavement under tables reached 42°C (108°F), and mean temperatures under the BTU armatures reached 37°C (99°F). This represented a 5°C (9°F) drop compared to under the tables (i.e. shaded pavement areas without vegetation). These findings on temporary, container-grown plant-based urban heat interventions represent a line of research that has not been scientifically and robustly investigated through peer-reviewed processes. The only existing paper to the knowledge of the author focused on trees (Rahman et al., 2023), as opposed to more rapid growing, annual species as were used in the study.

Finally, Chapter 6 [Human Behavior] comparing a BTU intervention-based outdoor classroom setting versus a conventional indoor classroom setting revealed that student classroom engagement was higher in the BTU outdoor classroom, as measured through student attention redirects, teacher evaluations of classroom engagement, and student classroom outputs for 4th and 5th grade students. This data aligns with previous research on the benefits of nature-based learning on student classroom engagement (Francis Norwood et al., 2021; Guardino et al., 2019; Kuo et al., 2018; Largo-Wight et al., 2018), while providing evidence that these benefits extend to temporary nature installations in atypical contexts like parking lots. Additionally, regarding perceptions of biodiversity and associated affective captioning in the BTU outdoor classroom, students selected photographs that featured biodiversity as their favorites (plant and insects), but their photo captions did not necessarily contain affective language. Among three grade levels, students in the oldest grade level were most likely to photograph insects. The application of participatory nature photography in the BTU outdoor classroom represented a novel and exploratory line of research and one where future work could explore its use as both a tool to study and shift children's perceptions of nature.

7.2 Limitations & Future Directions

The specific limitations and future directions of each experiment are flagged in the prior relevant chapters. This section explores broader limitations that cut across the interdisciplinary themes and pairs a discussion of these limitations with emerging future directions for research.

Participatory Process & Community Catalyzation

Expanding beyond the concept of BTU, T/t urbanism occurs through participatory processes among community members, on a spectrum of bottom-up to top-down approaches (Fig. 9). In its purest, most original form, T/t urbanism occurs as bottom-up, grassroots efforts.

The dissertation engaged with participatory processes with the partner school through a co-design framework that incorporated elements of this type of grassroots engagement. The overarching design of the study was a co-designed process with the partner art teacher who was involved in nearly every aspect of the project (e.g. research questions, structure of study, curriculum, recruitment, media outreach, etc.). The teacher designed a bespoke curriculum tailored to the research study that focused on nature photography in the two spatial contexts (BTU outdoor classroom and conventional classroom) and enlisted a locally renowned professional photographer's support in developing a YouTube instructional video for students. From a physical design perspective, the BTU planting armature designs emerged in part through a series of co-design workshops with the teacher's art students. Moreover, the teacher independently hosted a public art show featuring student photography from the study and co-hosted a community harvest event with the author at the end of the study (attended by ~50 community members; Fig. 55).

Figure 59: Community harvest event at the BTU classroom; Public art show of student photographs from the study

While this research contained many elements of bottom-up, grassroots partnership, in some ways it did not. As a researcher, the author initiated many of the discussions and ideas and was responsible for fabrication and most horticulture design decisions associated with the BTU intervention. A future study could explore how the typical bottom-up, problem-responding processes associated with T/t urbanism could be teacher-driven without the active involvement of an outside researcher. This noted, it remains unclear if true "bottom-up T/t urbanism" could ever occur in formal education settings, which have clearly defined systems of hierarchy and rules. Instead, T/t urbanism approaches that are more top-down or middle-out (e.g. municipal-driven efforts such as Barcelona's T/t urbanism-centered urban planning efforts; Schreiber, 2025) provide the clearest analogy to how this process might be best situated within the public schools.

Equally, the complexity of the specific BTU armature designs employed might be challenging for T/t scalability and these need further investigation. The eventual hope of the author is to release a simpler, open-source version of the BUT plans, and explore how their design, fabrication, and horticulture could situate intergenerationally between high school, middle school, and elementary school levels of education, either within or outside of formal curriculum. Conceptually this could draw from the skill-building, community empowerment efforts of groups like Tiny WPA and Girls Garage. However, an empirical exploration of these ideas was beyond the scope of this dissertation.

A larger fundamental question remains about the potential catalytic role of BTU in promoting longer term shifts towards schoolyard greening in the spirit of T/t urbanism. This study did not explicitly study shifts in stakeholder attitudes or associated longer term outcomes in schoolyard greening. Schoolyard greening requires significant time, resources, and community buy-in that ultimately were beyond the scale and scope of this study. In addition to the partner art teacher, the researcher did invite primary classroom teachers to use the BTU learning environment after the study was complete. The author was not able to track its usage systemically but was aware of multiple other classes (4+) using the BTU outdoor classroom. Additionally, anecdotally the partner school has installed two permanent outdoor classroom spaces since completion of the study and that the partner art teacher has spearheaded these efforts. These were supported in part by the district superintendent (see quote below), who visited the BTU installation during the research period. Longer term outcomes and impacts like these could be explored in future studies.

> *"Teachers don't want a stale classroom. They want to change things up. They want to have a new seating arrangement. They want to have the kids come in and think, 'Oh, something new today.' They get engaged to learn that way," he said. "And the pop-up outdoor learning space, it provides the same thing. It's a place to go to study something new and something different every day."*

Dr. Michael Richards
Harrisonburg Public Schools Superintendent
(McKenzie, 2023)

Temporal & Spatial Scales

T/t urbanism by its definition signifies impermanent changes that are short term. Yet it also limits the generalizability of any findings from a temporal perspective. For example, Chapter 4 [Technology] used annual plants as a model for insights into longer living perennial species; that assumption may not be valid as longer-lived plants could potentially behave differently than annual agricultural species under the same plant training experiments. Equally, Chapter 5 [Ecology] examined the impacts of the BTU intervention on surrounding ecology including insects. This represented a short period (~8 weeks), and thus the generalizability of the findings to longer term ecological processes such as insect population dynamics is limited. Finally, Chapter 6 [Human Behavior], explored student engagement and perceptions of the temporary biodiversity classroom intervention in a short window (3 weeks). The longitudinal behavioral response of the students in the BTU classroom may have differed from the short study period. Additionally, the seasonality of the research (late summer), limits the generalizability of the findings to other periods. A future, more robust investigation would explore different temporal scales and seasonality of BTU across all three knowledge domains.

Along with temporal limitations, the small spatial scale of the research limits the findings. For Chapter 4 [Technology], plant research occurred at the specimen-scale, while Chapter 5 [Ecology] examined insect and heat interactions at relatively small spatial scales from an ecological process perspective. It is unclear whether the findings scale to larger ecological contexts. Looking to the future, this body of research ultimately seeks to provide a foundation for future larger scale work to explore these temporal and spatial questions at site and landscape-scale. This will require deeper research into how BTU can metamorphose from the installation scale to more permanent, catalyzing/self-replicating solutions that draw from ecological and social theories of change.

Design, Technology, & Computation

The methods and technologies of design computation were employed throughout this dissertation, especially in the early stages of the work. Chapter 4 [Technology] focused on modeling of plant growth at the specimen scale. Building on this, the design and construction of the BTU itself utilized parametric form-finding methods to generate a configurable system, where multiple armature geometries were possible using standard components. In Chapter 6 [Human Behavior] an attempt weas made to analyze the large volume of student photographs (30,000+ images) through computational image analysis tools but was not found to be feasible due to image quality issues.

Arguably, the theoretical and critical role of technology (and design computation specifically) as one overarching theme for the dissertation could have been strengthened; in other words, was computation necessary to explore biophilic tactical urbanism? Perhaps not, as the body of work stands. Initially, the author expected the school partnership to be with STEM-based teachers and associated curriculum. This would have supported closer alignment with digital/physical computational approaches. For example, students in a plant biology module from science class could have collected data on plant training experiments embedded in the deployed BTU "STEM" armature (Fig. 35) and studied the fundamentals of plant physiology and behavior. The eventual partnership with an art teacher, while fortuitous in many ways, did not provide a straightforward platform for incorporating elements of science and technology into the human behavior research and associated co-designed curriculum in the BTU outdoor classroom.

Acknowledging these technological-integration limitations, there remains a large untapped potential for digital/physical tools (sensing, modeling, analyzing, and intervening) to support more in-depth and larger scale BTU research in the context of schools, linking the ideas of Chapter 4 [Technology] with human behavior and ecology. At a small spatial scale, this dissertation did not explicitly research the performance questions around the below ground attributes of containerized plant growth (i.e. pot size) but is a critical area to explore more deeply as it acts as a limit to overall plant growth. Parametric modeling of plant root behavior could inform future BTU applications. At a much larger scale, school buildings and schoolyards often follow common architectural and environmental typologies based on the period of construction (e.g. the International-style era that dominated U.S. school designs from the 1950s-1970s). Could the interaction between architecture and plant growth at the building envelope be modeled across these typologies, and how might this impact and align with socio-ecological elements in schools including curricula, human behavior, urban heat and climate change, biodiversity, and building performance? BTU as a temporary intervention tool could help develop and validate these models.

Linkages between biodiversity and human behavior

The connection between biodiversity observed and how students perceive this biodiversity remains an unanswered question; ecological data was collected on the presence of insects in response to different planting designs, while human perception data was independently collected via participatory photography. These data ultimately lived separately in the body of work but ideally would be linked. This would allow for deeper insight into the interplay between actual biodiversity and perceived biodiversity (a better measure of how people perceive biodiversity (Breitschopf & Bråthen, 2023; J. S. Wilson et al., 2016), as well as the ostensible role of environmental education in mediating this relationship. Finally, beyond education, the evidence continues to mount on the positive linkages between greenspace exposure (P.-Y. Nguyen et al., 2021; Reyes-Riveros et al., 2021) and bluespace exposure (Georgiou et al., 2021; M. P. White et al., 2020) and human well-being. Yet the connections between biodiversity specifically and well-being are not as clearly understood (Davis et al., 2025; Marselle et al., 2021; Robinson et al., 2024) and could also be further elucidated.

When designing both the ecology and human behavior studies, there were several outstanding questions of the author about insects. 1) Would insect show up?, 2) What types of insects?, and 3) How would 5-11 years old respond to them? Insects did appear, and were surprisingly relatively diverse (12 families, including 6 genera of Hymenoptera (bees, wasps, ants)) compared to a parking lot baseline of near zero (1 family with 2 genus of ants). Equally surprising were students' reaction to the insects. By and large, students were fascinated by them (and not overly fearful) based on the author's observations. Some students did express fear/disgust at times, but of 8 participating classrooms only one "Ah!!!….run!" screaming fit occurred. To the contrary, many students were fearless and would deeply engage with their photographic subjects, at times getting extremely close to bees and wasps—within 6 inches. Thankfully no stings occurred during the research. Drawing from the urbanization–disgust hypothesis (Fukano, Y., & Soga, M., 2021), future questions about how and when negative attitudes about insects form and among different types of insects in urban areas could be explored. Moreover, the role of nature photography may provide a novel research and education tool for affecting these attitudes.

A future study could more explicitly engage with both biodiversity and human behavior levers in the BTU dynamic. For example, this might include manipulating planting designs, the broader ecological matrix of the landscape including habitat patches and corridors from a landscape ecology theoretical perspective, and other ecological elements to generate more complex ecologies beyond three planting designs (low, medium, and high biodiversity; Fig. 36). Equally, children's interactions with the BTU system and associated biodiversity could be explored through more rigorous behavior methods. Human subjects research methods in Chapter 6 [Human Behavior], were ultimately limited by the decision to structure the study design around "normal educational practice." This expanded the sample size, but prevented the use of more complex instruments and measures such as connectedness to nature (Mayer & Frantz, 2004), child-friendly psychological scales, human biophysical data, etc. Future research could incorporate these more intensive methods, which could help develop the linkages between 1) biodiversity and 2) the human experience of biodiversity.

For example, student classroom engagement is a complex behavioral process involving mental, physical, and social processes among pupils, their teachers, the specific pedagogical content, and environmental attributes. For this dissertation, student classroom engagement was defined as a "student's ability to pay attention and stay on task in class" (Miller et al., 2021). From a psychological perspective, engagement can be modified by cognitive changes through Attention Restoration Theory (ART; Kaplan 1995) or mood and stress changes through Stress Reduction Theory (SRT; Ulrich et al. 1991). Biophilic design frameworks explicitly or implicitly acknowledge these ideas in their frameworks (see Chapter 2.3).

For this study, no measures of cognitive or mood/stress were included and this represents a limitation. Both ART and SRT were likely factors with the increased classroom engagement associated with the BTU classroom condition. For example, throughout the outdoor class period students were able to experience at least three dimensions of ART (being away – a new space; fascination – dynamic, living nature installations; extent – exploration of the micro world through the lens of a camera). Typically, ART and SRT are theoretical positioned as breaks to cognitively taxing and/or stressful periods (i.e. a walk in a park after a stressful day). How these processes occur during the actual periods of focused attention or stress (i.e. classroom instruction) is less clear. In this study, it could be argued that art class effectively provides a break from core classroom instruction, acting as a restorative environment that facilitates ART and SRT mechanisms.

7.3 Towards Schoolyard Greening Through Biophilic Tactical Urbanism

In the article "A national research agenda supporting green schoolyard development and equitable access to nature" (Stevenson et al., 2020), the authors propose 1) a vision for schoolyard greening as a tool for broader community benefits and 2) a research program to help achieve this vision. Absent in this vision is the potential for curriculum-aligned, community-drive technological interventions to drive change towards preferred spatial futures. Public schools are by and large resource-limited, and these resources are directed heavily toward their primary mission–the education of children. This dissertation begins to explore how these limitations could be repositioned as strengths, using BTU to provide a tool for bottom-up collective redesign of these critical community spaces; schoolyards are not just for children, but also act as "public parks" informally or formally. There remain many questions on how BTU could help achieve these lofty goals. Engaging multi-level participatory processes and incorporating emerging socio-ecological technologies, both situated in the programmatic context of schools, are likely critically important.

From this diverse, hybrid body of research, numerous possibilities for future work emerge to support the potential for scaling these ideas that extend beyond the primary scope of the dissertation:

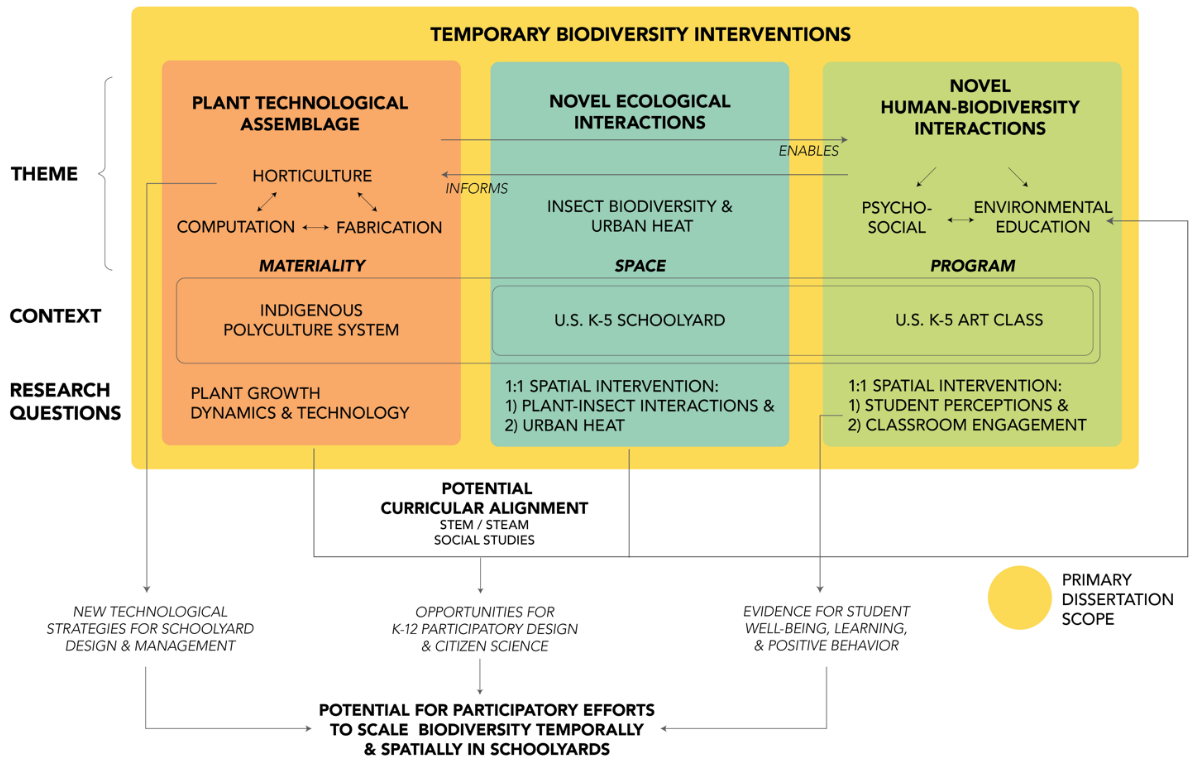


Figure 60: Interdisciplinary framework for dissertation

- **Greater Curricular Engagement:**

  How might the design and science elements of this work more fully align with K-12 curricula? This represents a large opportunity for scaling the concept of BTU (and greening schoolyards more broadly) through participatory/citizen science processes that are rooted in experiential learning and constructivist theories. From the sciences, efforts such as Project Learning Tree provide models for how teachers might engage with their schoolyards as living classrooms in science education (e.g. plant growth and behavior), and beyond. The 3 Sisters itself provides a rich opportunity for more in-depth educational materials, and indeed the researcher was surprised at the dearth of teaching materials publicly available. The indigenous polyculture system provides opportunities for STEM, social studies, and STEAM curricular tie-ins (See Fig 56), that directly match to existing state-level standards of learning in Virginia, and likely the requirements of other states.

GRADE	SUBJECT MATTER	SOL ALIGNMENT	ASSIGNMENT
Mulitple	Art	Multiple	Nature-oriented Creative Expression
2nd	History & Social Sciences	2.2, 2.4d, 2.12b*	Native Studies
4th	Science	4.2 & 4.3**	Plant Growth/Form Experiments
TBD	Design	N/A	Garden Co-Design

2.2 The student will compare the lives and contributions of three American Indian cultures of the past and present, with emphasis on the Powhatan of the Eastern Woodlands, the Lakota of the Plains, and the Pueblo peoples of the Southwest.

2.4 d) understanding the relationship between the environment and the culture of the Powhatan, Lakota, and Pueblo Indians.

2.12 b) have diverse ethnic origins, customs, and traditions, make contributions to their communities, and are united as Americans by common principles.

4.2 The student will investigate and understand that plants and animals have structures that distinguish them from one another and play vital roles in their ability to survive. Key ideas include
a)the survival of plants and animals depends on photosynthesis;
b)plants and animals have different structures and processes for obtaining energy; and
c)plants and animals have different structures and processes for creating offspring.

4.3 The student will investigate and understand that organisms, including humans, interact with one another and with the nonliving components in the ecosystem. Key ideas include
a)interrelationships exist in populations, communities, and ecosystems;
b)food webs show the flow of energy within an ecosystem;
c)changes in an organism's niche and habitat may occur at various stages in its life cycle; and
d)classification can be used to identify organisms.

Figure 61: Three Sisters as curriculum / Virginia Standards of Learning Alignment

From a design perspective, the design, fabrication, and associated horticulture of BTU-type systems provides hands-on opportunities for experiential learning. Similar pedagogical models such as Tiny WPA and Girls Garage, which are independent non-profit-based efforts, demonstrate how tactical urbanism-oriented, maker/skill-building programs could empower youth to improve and activate their environments. How these kinds of models nest within formal education will differ -- vocational-based programs (e.g. shop class) could provide a mechanism. Equally, an intergenerational/inter-school approach, whereby high school/middle school students engage in more advanced design (and science) aspects of BTU fabrication and then deploy their work to middle/elementary schools.

- **Biodiversity, Plant Technology, & The Built Environment:**

This work focused on the programmatic context of K-12 education. While there are specific contextual aspects of formal education settings, the technical research into plant growth and biodiversity could theoretically apply to other urban contexts including parks, streets, and other built environments. Cities are increasingly looking for ways to incorporate nature into their spaces for ecosystem services benefits. BTU interventions could serve as steppingstones for catalyzing infrastructure changes in the spaces. More ambitiously, a temporary biodiversity approach might provide a testing ground for more highly attuned systems such on-structure vegetation (i.e. green roofs, green walls).

- **School Grounds as Hubs of Ecological Resilience**

U.S. Public school infrastructure plays a unique role in environmental resiliency as it is often one of the largest land holdings of local governments, providing an important lever for energy and climate, biodiversity, water stewardship, etc. In other words, public schools provide an applied testing bed for One Health priorities (CDC, 2024) where the linkages between human, animal, and environmental health and well-being can be explored—with important implications for the communities they serve. The schoolyards of public education specifically are low hanging fruit for these efforts, as they are often large, underutilized, and improvements are less expensive than building changes. Moreover, they have the potential to provide multiple benefits (see Fig 56B). Imagining schools as hubs for broader ecological resilience will require an interdisciplinary, hybrid integration of socio-technical approaches that blend ecology, education, infrastructure, and more. The BTU approach in this body of work begins to explore these linkages from design, programmatic, and ecological lenses.

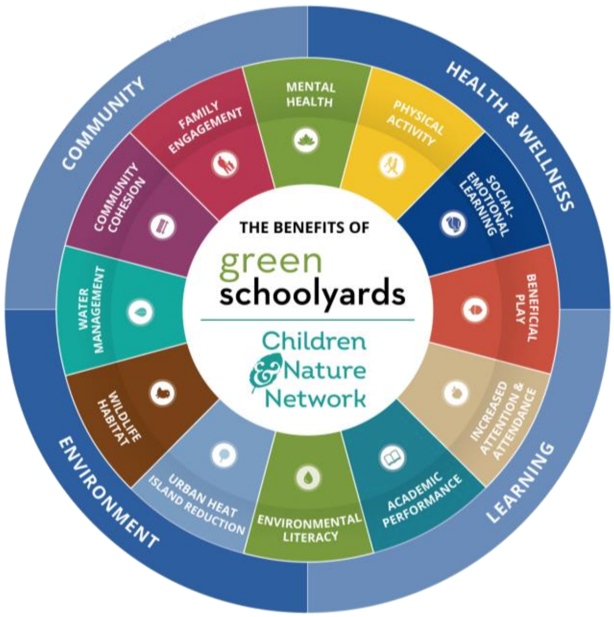


Figure 62: Multi-benefit framework for the benefits of green schoolyards (Children & Nature Network, 2022)

This work only scratches the surface of these questions and is a proof of concept for future work. It represents an ambitious, interdisciplinary linkage of science and design that points towards larger scale efforts to improve the outdoor educational environments of U.S. children, non-humans, and beyond.

Appendix 1: Emergence of the BTU Design

The following is a record of the design process that resulted in the BTU design and which unfolded over several years during the PhD process.

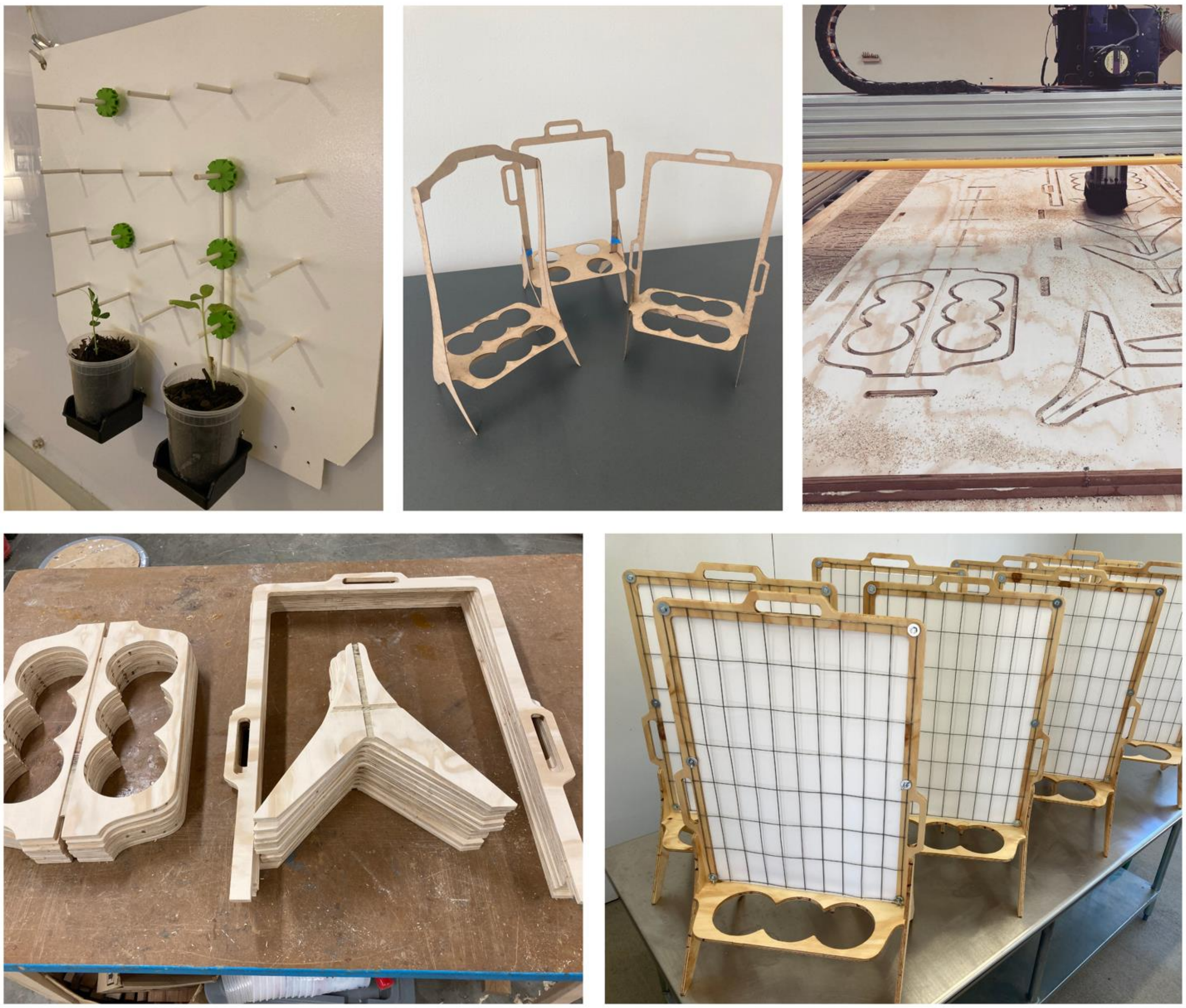


Figure 63: Phase 1 Early armature designs (2021). This work tested a 3.5’ tall modular plant armature system.

Figure 64: Phase 1 growth experiments with timelapse photography

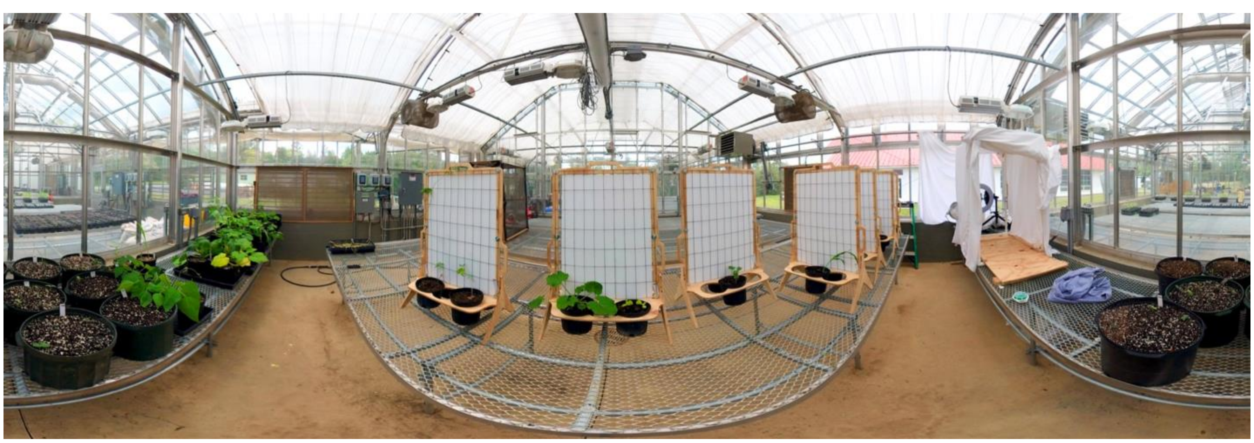


Figure 65: Phase 1 Greenhouse set up

Figure 66: Phase 2 Corn and squash growth experiments (2022). Results from these experiments later became part of Chapter 4: Cultivating Computationally.

Figure 67: Phase 3 Biomaterials Building Exhibition (2022). The aim was to construct a 3 Sisters installations that demonstrated both the interactions between the three plants, and the effect of tropisms on their combined growth.

Figure 68: Phase 4 BTU armature prototypes. These prototypes explored full scale dimensions and planting palette design.

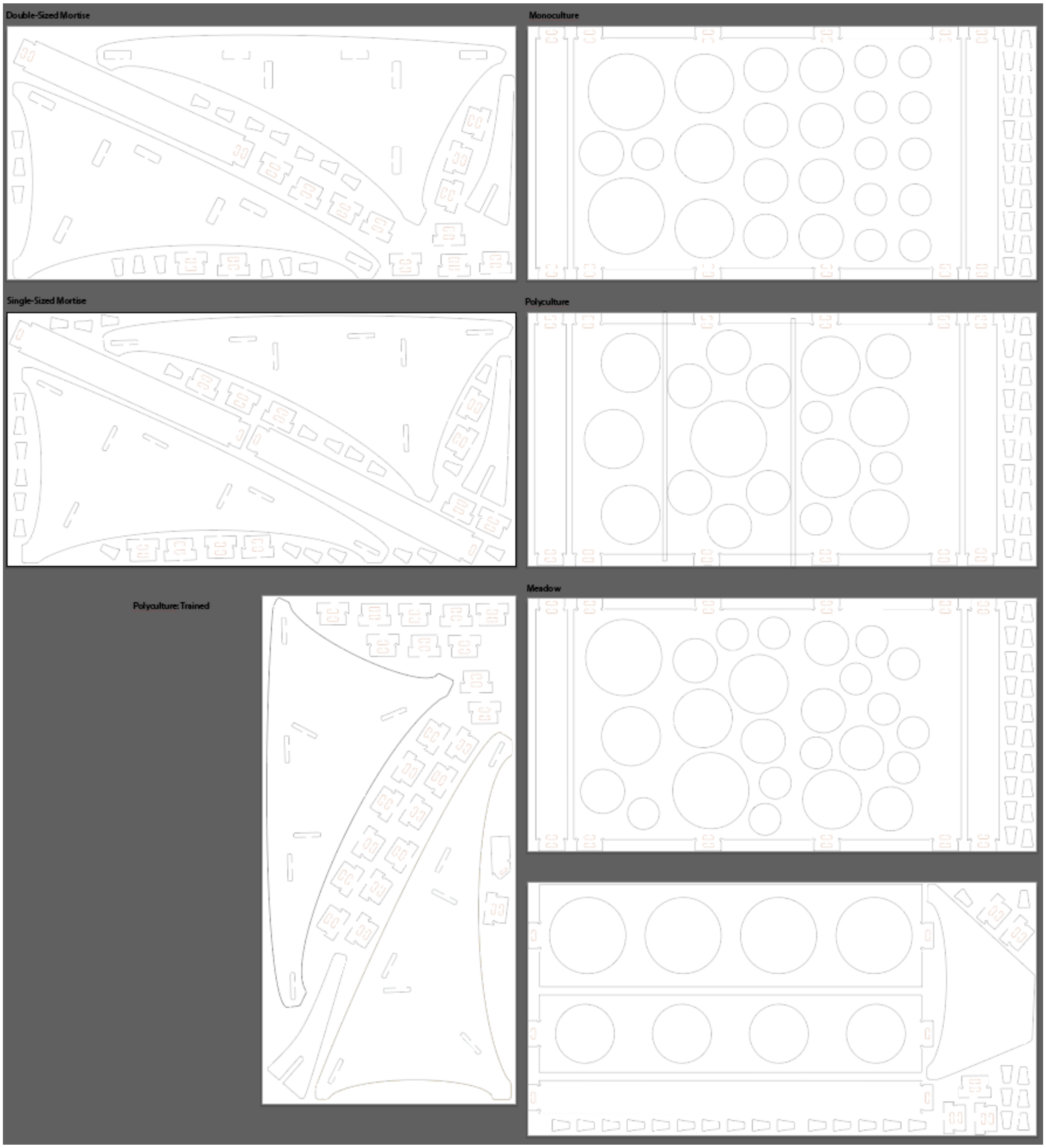


Figure 69: Phase 4 BTU plans for the different planting designs.

Figure 70: Phase 4 BTU armature fabrication

Figure 71: Phase 4 BTU installation in the school parking lot.

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Figure 5: Children and Nature Network, specific credit unknown

Figure 8: Kim Dovey

Figure 9:

Figure 10: Rebar

Figure 11: Linda Tegg

Figure 13 (Clockwise): Baubotank Footbridge - Ferdinand Ludwig; Bee Conservancy - Harrison Atelier; Fab Tree Hab - unknown; Platform for Humans and Birds - unknown

Figure 15: MAS Studio Cut Join Play - Iker Gil

Figure 16: Unknown, historic postcards

Figure 18: Bosco Verticale - Raban Haajik; MFO Park - Joachim Kohler Bremen

Figure 20: Duhamel du Monceau

Figure 21: espalier -JP Mathh, bonsai - LP2Studio, lucky bamboo - Netsnake

Figure 22: Three Sisters diagram - Lopez-Ridaura, S., Barba-Escoto, L., Reyna-Ramirez, C. A., Sum, C., Palacios-Rojas, N., & Gerard, B.; Three sisters planted - Archivo Gráfico

Figure 30: Clockwise “Archipelago” - Jerónimo Hagerman (https://arquine.com/ 2015). “Bee Connected,” the Spatial Morphology Group at Chalmers (https://www.mareldarkitektur.se/work/bee-connected/ 2016). “Tiles,” Thibault Faverie, Paris France; “Tactical Urbanism,”(https://www.urbangardensweb.com/, 2015). Barcelona, Spain (https://www.metropolis.org/ 2019); “Build a Better Block,” Dallas, TX (https://nextcity.org/ 2015). “Layfette Elementary School Science Garden & Outdoor Classroom,” Seattle, WA (https://lafayettees.seattleschools.org/academics 2016).

Figure 31: Landscape ecology typologies, providing spatial inspiration for micro-scale BTU interventions (Dramstad et al., 1996)

Figure 41: T-l image: Steve Rhodes, All others: Street Lab)

Figure 53: Anonymous student photographs