Using Sculpture to Create Artificial Habitat Structures

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CONTENTS

1. INTRODUCTION

This interdisciplinary research project develops and explores an experimental ecological art approach called *habitat sculpture*. In this approach, outdoor sculpture installations create artificial habitat structures for non-human organisms in human-occupied areas. Artificial habitat structures are human-made objects that replicate important physical structures that organisms utilize for various functions in nature (Watchorn *et al.*, 2022). Common examples include bird nest-boxes, bat nest-boxes, beehives, insect hotels, and artificial reefs. Rather than replicate singular structures, habitat sculpture installations will include multiple structures and multiple elements of habitat. In this way they seek to provide for natural communities and species assemblages rather than singular target species. The primary goal of this thesis project is to assemble the latest scientific research on habitat structure creation and translate that information into practical usage for sculpture and sculpture installations. By incorporating habitat structures into sculpture installations, novel artistic, scientific, and conservation opportunities are made possible.

During this research, multiple habitat sculpture installations were created to explore different techniques and methods in practice. The goals of these pieces, and of habitat sculpture in general, are: *(i)* to play a tangible part in altering the ecology of human-occupied areas; *(ii)* to facilitate dialogue and education about nature in developed areas; and *(iii)* to create visually and conceptually compelling artistic interactions between sculptures and non-human organisms. Melding together habitat structures with artistic forms and public installations create synergies between the ecological, social, and artistic goals (Figure 1).

Artificial habitat structures have long been used for a variety of cultural and economic purposes, but researchers and conservationists are now looking to them to boost and sustain wild populations where natural habitat structures are limited (Cowan *et al*., 2021; Watchorn *et al.*, 2022). As researchers seek to better understand natural and artificial habitat structures, new possibilities and drawbacks for using these structures in conservation are being discovered (Croak *et* al., 2010; Lindenmayer *et al*., 2017; MacIvor, 2017; Parker *et al*., 2022). This research seeks in part to contribute a new interdisciplinary perspective to this endeavor. Sculpting artificial habitat structures in a fine art setting yields new and creative techniques for habitat creation not practical or possible in traditional construction or manufacturing settings. The slow, handcrafted nature of sculpting can allow for structures that are higher quality and more individualized than mass produced structures. New techniques and creative thinking around the issue can also lead to innovation and discovery. Habitat sculptures are more suited to some human-occupied areas than utilitarian habitat structures because they account for aesthetics and can be customized based on location and community preferences. They also bring in alternative sources of support and funding through arts organizations and community groups (Spaid, 2002; Art21.org, 2004).

The biggest contribution that habitat sculptures can make to nature conservation comes not from their direct contribution of habitat, but from their social impact; namely, their ability to educate and spur dialogue about nature in human-occupied areas. Habitat sculptures have this feature in common with many ecological art approaches (Spaid, 2002; Schoenacher, 2013). However, the habitat sculpture approach differentiates itself by showing the viewers functional habitat structures in action, and more importantly by allowing the public to see real wild organisms who are interacting with the sculptures. The contribution of habitat in these projects may not have a large impact on ecosystems, but their ecological functionality is an integral part of the sculptures ability to facilitate dialogue and education. For most people, seeing a wild animal using an artificial nesting cavity in a habitat sculpture would be substantially more engaging and memorable than simply reading or hearing about it. The visual artistry of the sculptures themselves also draw attention to installations, furthering the goals of social engagement. This synergistic feedback between the social, ecological, and artistic aspects of the habitat sculpture approach are shown in Figure 1.

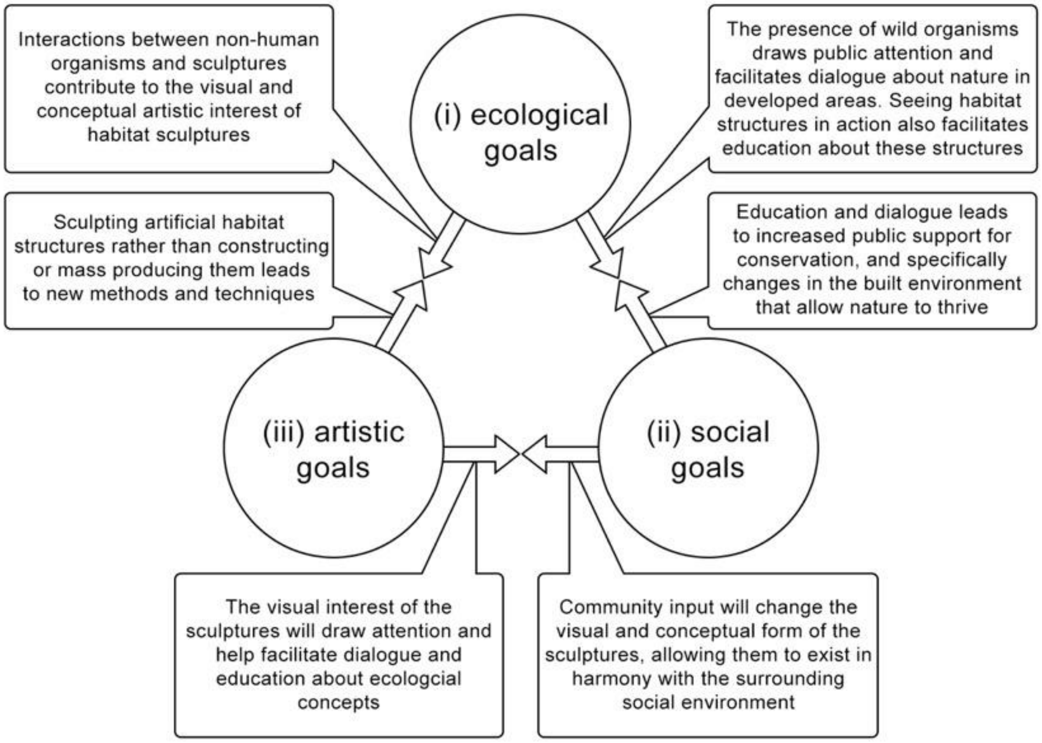

Figure 1. Interdisciplinary synergies between the ecological, social, and artistic goals of habitat sculpture. The goals are (i) to play a tangible part in altering the ecology of human-occupied areas; (ii) to facilitate education and dialogue about nature in developed areas; and (iii) to create visually and conceptually compelling artistic interactions between sculptures and non-human organisms.

The physical and visual emphasis of the habitat sculpture approach differentiates it from many other ecological art approaches. Many of these approaches focus on practical impact and conceptual artistry rather than visual form, as in Mel Chin's 1991 piece, *Revival Fields* (Art21, 2004; Vesna, 2006). The visual interest in these approaches often consists of landscaping, informational panels, or supplemental works that are displayed at galleries and other venues off-site (Spaid, 2002; Schoenacher, 2013; Geffen, 2022). In contrast to these approaches, the integration of sculptural form with ecological functionality in habitat sculptures creates many exciting artistic possibilities. Other ecological artists whose work can be considered habitat sculpture are reviewed in section 2.3. Another benefit of using sculpture, other than visual interest and conceptual potential, is that works of public sculpture have an accepted place in the built environment. We are accustomed to seeing sculptures in gardens, public squares, parks, museum grounds, etc. Habitat sculptures leverage this culturally allotted space in populated areas to create habitat structures where they otherwise might not be accepted. In this way, habitat sculpture installations function as catalysts for the resurgence of nature in the most built-up parts of the built environment.

While the habitat sculpture approach has precedence in ecological art (section 2.3), the research and material exploration done in this thesis project has produced new techniques and methodologies for successful creation of these sculptures. While the primary purpose of this research was to gather the necessary information for me as a sculptor to personally create habitat sculpture installations, I hope that other artists and designers who are interested in creating work like this can use the information synthesized here to do so. This research is focused on the geographical region of Downeast Maine (USA) and the northeast USA because that is where my sculpture installations are based. However, my hope is that this research provides a template that can be applied to human-modified environments anywhere in the world by focusing on the local species and habitats involved. More artists pursuing this approach in collaboration with scientists could lead to insights and discoveries about artificial habitat structures used for conservation purposes. There are clear and reciprocal benefits for human society and ecosystems in human-occupied areas that could be attained with the adoption of this approach, as well as exciting artistic opportunities that can be explored by ecological artists.

1.1 SPECIAL CONSIDERATIONS AND LIMITATIONS

For all the interdisciplinary synergies this approach provides, there are also disadvantageous interactions between its divergent ecological, social, and artistic goals (Figure 2). Habitat sculpture projects must thoughtfully balance these tensions and employ certain practices to avoid unintended social and ecological outcomes. These practices include 1) proactive design to guard against known risks, 2) monitoring programs to look out for problematic organisms, 3) maintenance to keep sculptures in working order ecologically and aesthetically, 4) iteration and amelioration to address issues head on, and 5) removal if issues cannot be resolved.

An inherent tension between the ecological goal of increasing wild organism populations and the social goal of increasing support for nature conservation comes from the possibility of attracting pests and nuisance animals. Fear of nature and particular organisms is prevalent in our society, especially in places like cities where residents may have very limited exposure to non-human organisms (Kotze *et* al., 2011; Colding, 2011). While the habitat sculpture approach seeks to change these attitudes in part through exposure to nature, certain organisms are more likely to cause fearful backlash than thoughtful dialogue. Risks to human health posed by mosquito-borne pathogens, economic damage done to wooden structures by termites and carpenter ants, and predation of pets by animals like foxes and raccoons are all serious issues to be accounted for (Yee, 2008; LaDeau *et al*., 2013; Rupprecht, 2017; Santos, 2020). These specific threats are discussed further in section 3. These issues can be addressed in the design process by purposefully excluding problematic organisms. Robust monitoring, maintenance, and iteration should all be employed to ensure installations do not become sources of harm, thereby damaging the social support for nature in developed areas that they seek to build.

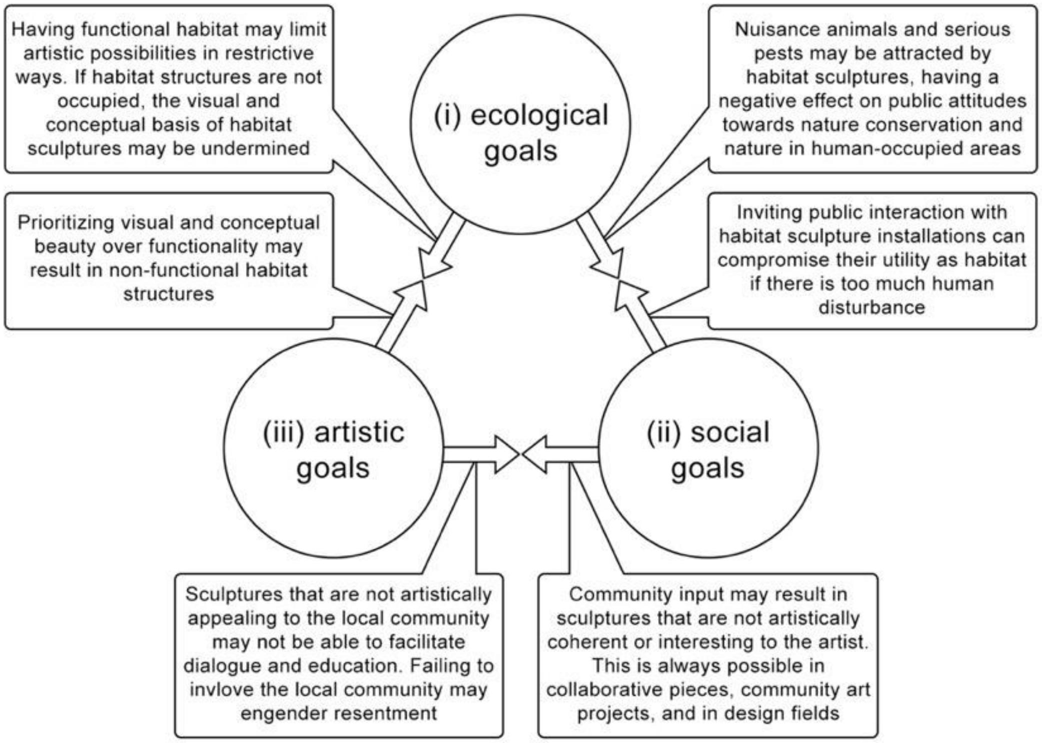

Figure 2. Disadvantageous interactions between the ecological, social, and artistic goals of habitat sculpture. Monitoring, maintenance, iteration, and amelioration will be necessary to avoid unintended ecological, social, and artistic outcomes.

Even if habitat sculpture installations avoid attracting problematic organisms, there is an inherent conflict between housing wild creatures in the sculptures and inviting the public to interact with the sculptures. Many wild organisms are intolerant to human disturbance, and some will avoid even the smallest hint of human presence (Rosenzweig, 2003). This fundamental tension can be ameliorated in two ways: first by targeting species that can tolerate human disturbance to some degree, and second by minimizing the amount of direct human disturbance experienced by sculptures through landscaping and barrier design that keep people a safe distance from wild organisms. Further mitigation of this tension is discussed in section 3.6.

There are serious ecological risks that come from artificial habitat structures, independent of whether they are a part of a habitat sculpture installation (Cowan *et al*., 2021; Watchorn *et al.*, 2022). Research into using artificial habitat structures for species conservation is an emerging area of study, and many methods and techniques that are being employed in the field lack rigorous evidence. Many studies that have been conducted warn of serious risks and perverse ecological outcomes (MacIvor & Packer, 2015; Lindenmayer *et al*., 2017; Maziarz *et* al., 2017; Geslin *et al*., 2020). When a habitat structure successfully attracts an organism, but the surrounding environment is not conducive to its survival, the structure becomes an *ecological trap* (Battin, 2004; Robertson & Hutto, 2006; Hale & Swearer, 2016). This can occur when the area immediately surrounding the structure does not have enough food, water, or other necessary resources to sustain an organism. It can also happen when a habitat structure or surrounding environment contain unnatural levels of predation (e.g., domestic cats), parasitization, or other detrimental factors (e.g., vehicle traffic, disturbance, temperature extremes). Habitat sculptures can account for these risks by provisioning the installation site with the necessary resources for target organisms, or by making sure they are within a reasonable distance from the site. They can also select sites to specifically minimize the threats listed above. Monitoring, maintenance, iteration, and removal must all be utilized to ensure that habitat sculpture installations do not become ecological traps.

Artificial habitat structures can also go awry when they are utilized by invasive species at the expense of native organisms or target species (MacIvor & Packer, 2015; Geslin *et al*., 2022). Habitat sculptures may be at especially great risk of this outcome because of their novel forms, and their locations within human-occupied areas. Evidence indicates that invasive species may be inherently more adept at exploiting novel habitats, including artificial habitat structures (Lowry *et al.* 2013; MacIvor & Packer, 2015). Human-occupied areas like cities also have higher densities of non-native and invasive organisms, making it more likely that they may occupy habitat sculpture installations in these areas (Potter & Mach, 2022). Specific strategies can be employed against specific invasive species, such as excluding their preferred habitat structures and conditions. In the case of artificial nesting cavities for bees in North America, researchers recommend not creating cavity diameters of 8 mm and above to exclude the invasive bee

Megachile sculpturalis (Geslin *et al*., 2020). A variety of invasive animal species can also be discouraged by excluding non-native plant species from the vicinity of habitat structures, and making sure ample native vegetation is present (Tallamy, 2007; MacIvor & Packer, 2015). Again, monitoring, maintenance, and modification of problematic structures must be employed to ensure habitat sculpture installations are not hosting invasive species populations at the expense of native populations.

Although there are potential risks, the small scale of habitat sculpture installations means that these risks can be monitored and managed more closely than in large-scale interventions. If the monitoring and mitigation efforts highlighted above are at the forefront of the planning, design, and implementation of habitat sculpture projects, negative outcomes can be avoided. Detailed protocols for monitoring and assessing habitat sculpture installations are reviewed in section 5.

1.2 ARTISTIC VISION

I see habitat sculpture installations as visions into a future where human-occupied areas host greater abundances and diversities of living creatures than they currently do. In such a future, cultural, social, and economic relationships would be radically altered, along with the very fabric of the built environment. Such changes would require massive effort and will, and are probably a long way off, if they come at all. Habitat sculptures leapfrog the current moment by creating small bubbles where nature and the urban environment are intertwined in ways that are currently impossible on larger scales. In habitat sculpture installations this vision of a possible future is not only depicted, as it would be in a painting or relief, but it is actively pursued. By giving sanctuary to a diversity of wild creatures in the built environment, a living window to a more harmonious existence is opened to the human viewer. Sculptures interacting with wild creatures create potent images and examples of the human-made and the natural accommodating each other and thriving.

The artistic content of habitat sculpture installations will vary from project to project, but the component of providing habitat structures in purposeful and beneficial ways will always be present. I have created multiple habitat sculpture installations as part of this thesis to illustrate and test new methods and techniques (section 4). There are a variety of visual and conceptual themes in these installations including a sculptural food web diagram that surrounds a dead tree, a miniature cityscape which organisms can inhabit as literal and metaphorical residents, and abstract human forms with habitat features imbedded in their bodies. In all these cases non-human organisms are invited to inhabit and interact with the sculptures, but the exact form of this interaction varies widely. I hope that these examples show the artistic potential inherent in the habitat sculpture approach and can spur readers to imagine further possibilities.

2. LITERATURE REVIEW

This literature review will cover environmental issues, conservation approaches, ecological design approaches, social science frameworks, and artistic approaches that habitat sculpture draws on. The first section will give environmental background and cover relevant ecological concepts such as urban ecology, reconciliation ecology, and artificial habitat structures. Ecological design topics such as urban planning, biomimicry, ecological engineering will be covered next. Lastly, this section will review artistic precedents set by artists in the contemporary ecological art movement such as Mel Chin, Jason deCaires Taylor, Lynne Hull, and Jackie Brookner. The bulk of the research reviewed for this thesis was on detailed information about habitat structures, both natural and artificial. This information will be examined in-depth in section 3, where it will be translated into new techniques and methods for habitat sculpture creation.

2.1 ENVIRONMENTAL BACKGROUND

The current human-caused decline of biodiversity and species abundance is one of the most urgent social and environmental problems facing the planet. We are presiding over an immense loss of global biodiversity on par with the five great mass extinction events in Earth's history (Ceballos *et al*., 2020). It is possible that even with current mitigation efforts, two thirds of all terrestrial vertebrates could become extinct by the end of the century (Raven *et al*., 2011, Cafaro, 2015). Already wild animals account for only 6% of terrestrial vertebrate biomass, with humans and their livestock accounting for the other 94% (Bar-On *et al.*, 2018). Invertebrates are faring no better, with insect populations showing declines ranging from 45% to 75% across various taxa, sometimes dubbed the "insect apocalypse" (Cardoso *et al*., 2020; Wagner 2020). The evidence is increasingly clear that radical action is needed on multiple fronts to head off a global loss of biodiversity that would harm human society immeasurably and take the Earth millions of years to recover from (Cafaro, 2015; Díaz et al., 2019; Cowie *et al*., 2022).

According to the United Nations report on biodiversity and ecosystem services, ecologically destructive land use is the leading cause of population decline and species loss (IPBES, 2019). Stopping and reversing harmful land use practices should consequently be among the top priorities for conservationists, despite the much larger amount of public attention paid to the destructive effects of pollution and future climate change on the natural world (Maxwell *et* al., 2016; Díaz *et al.*, 2019). Multiple authors have highlighted the need to fight the social values and economic behaviors that drive destructive land use as part of the effort to combat it (Cafaro, 2015; Maxwell *et* al., 2016; IPBES, 2019; Díaz *et al.*, 2019).

According to United Nation's *State of the World's Forests 2020* report, the leading causes of global deforestation are agriculture, urban expansion, infrastructure expansion, and mining (FAO & UNEP, 2020). Urbanization accounts for only a small percentage of global land cover, but is expanding rapidly in ecologically sensitive areas, such as forests, grasslands, wetlands, and global biodiversity hotspots (Döös 2002; Seto *et al*., 2012; Chen *et al*., 2020b; Simkin *et al*., 2022). It is therefore necessary not only to curb the expansion of developed areas into natural ecosystems, but to actively conserve nature and improve biodiversity inside urban areas (Rosenzweig, 2003; Deslauriers *et* al., 2018; FAO & UNEP, 2020). Innovative work is currently being done by scientists and conservationists to improve the habitat capacity of human-occupied areas (e.g., cities, towns, suburbs), which were traditionally considered to have little ecological value (Miller & Hobbs, 2002; Rosenzweig, 2003; Standish *et al*., 2013).

2.1.1 Urban ecology

Ecosystems in cities have traditionally been viewed by ecologists as not worthy of scientific study because of human interference (McDonnell, 2011). This view has contributed to a devaluing of nature in human-dominated landscapes among scientists, environmentalists, and the public (Niemelä *et al*., 2011). *Urban ecology* is a field that got its start in the 1970's but only started gaining real traction in the scientific community in the late 1990's (McDonnell, 2011). The view among contemporary urban ecologists is that rather than ecological wastelands, cities consist of unique ecosystems that are just as amenable to scientific study as ecosystems in 'undisturbed' environments. If ecology can be defined as 'the study of organisms and their environments' (McIntosh, 1985), then for urban ecologists the environment also includes things like artificial structures, economic systems, and social and cultural dynamics. Because of these complex interacting factors, urban ecology is an inherently interdisciplinary field involving both the sciences (physical and social) and the humanities (McDonnell, 2011).

The study of urban ecosystems has turned up many surprising findings in the past two decades that have upended traditional assumptions and created a much more complex and nuanced picture of cities. For instance, biodiversity in cities may be higher than in surrounding natural areas under certain circumstances; cities can even host substantial numbers of rare and threatened species (Pickett *et* al., 2008; Ives *et al*., 2016). It has also become clear that urban areas are both dependent on nature (i.e., ecosystem services) and have huge impacts on the health of ecosystems outside their borders (Standish *et al*., 2013; Ouyang *et al*., 2018). Conservationist and restoration ecologists have begun to see work in human-occupied areas like cities as opportunities to increase landscape connectivity, proactively manage invasive species, and mitigate negative ecological influences on adjacent lands (Miller & Hobbs 2002). As well as the direct ecological benefits of habitat conservation and restoration, sustaining nature in the human-occupied environment benefits conservation efforts by increasing public support and awareness of environmental issues (Kaplan & Kaplan, 1989; Miller & Hobbs 2002; Colding, 2011; Kotze *et al*., 2011).

Cities are conceptualized by many urban ecologists as matrices or mosaics of many differing land-use and surface cover types (Pauleit & Breuste, 2011). This intense spatial heterogeneity is thought to be one of the driving forces shaping urban ecosystems, and one of the primary factors differentiating them from natural ones (Pickett *et al*., 2016). Management actions broadly focus on increasing ecologically hospitable patches, protecting remnant patches of undisturbed nature, and enhancing ecological connectivity by creating hospitable corridors between patches (Niemelä *et al*., 2011). Management actions to increase ecologically hospitable conditions include decreasing impervious surface cover, naturalizing waterways, increasing vegetation, including a variety of vegetative successional stages and structural heterogeneity, and protecting rare habitat types such as large old trees (Niemelä *et al*., 2011).

Researchers and planners also focus on the effects of urban ecosystems on civil and socioeconomic interactions (Standish *et al*., 2013). The study of urban ecology is inextricably linked with political decision making and management actions since these actions are the main drivers of ecosystem dynamics within cities (Niemelä *et al*., 2011). The physical conditions of cities are not immutable forms handed down by God, but the results of decisions that are being made every day. Many urban ecologists see it as their duty to inform planners and decision makers about the ecological effects of their actions, and to advocate for ecologically beneficial approaches (Niemelä *et al*., 2011).

The habitat sculpture approach draws on the findings and frameworks of urban ecology. Understanding the factors that affect species diversity and abundance in cities enables habitat sculpture installations to change ecological conditions. Understanding and analyzing the wider ecological networks in which habitat sculptures reside will help ensure that installations contribute positively to urban ecosystems. Specific interventions tested by urban ecologists that are relevant to this thesis research include the addition and protection of dead wood resources (Gaston *et* al., 2005; Horák, 2018); providing resources for pollinators (MacIvor *et al*., 2014; MacIvor & Packer, 2015); general insect conservation (New, 2018); increasing bryophyte and epiphyte vegetation on hard surfaces (Lundholm, 2011; Udawattha *et al*., 2018); using residential gardens to enhance biodiversity (Gaston *et* al., 2005; Davies *et al*., 2009; Miller *et* al., 2015; Levé *et* al., 2019; Majewska & Altizer, 2020), and providing artificial nesting cavities for vertebrates in urban areas (Honey *et al*., 2021). Another field of research that will be applicable to this project, and focuses specifically on the human-modified environment, is called reconciliation ecology.

2.1.2 Reconciliation Ecology

Michael Rosenzweig (2003) defines the term reconciliation ecology as the theory and practice of sharing our habitat deliberately with other species with the goal of maintaining species diversity. The need for reconciliation ecology stems from the assumption that there is not enough pristine space left on the planet to sustain the diversity and abundance of life that currently exists (Rosenzweig, 2003). This assumption is derived through an analysis of species-area relationship curves and human land-use patterns (Rosenzweig, 2003). If conservation and restoration cannot provide enough space to maintain our current cohort of organisms, then we must leverage the space that humans occupy to provide the needed habitat space (Rosenzweig 2003). Many organisms will never be able to thrive in human-occupied areas because of their low tolerance for disturbance (known as *urban avoiders*), but many others can do so if certain modifications are made to the built environment (known as *urban adapters* and *urban exploiters*; Rosenzweig, 2003; Ouyang *et al*., 2018). Increasing habitat in human-occupied areas also yields important ecological benefits such as landscape connectivity, and benefits to human health and wellbeing (Fuller *et* al., 2007; Jansson *et al.*, 2009; Berthier *et al.*, 2012; WHO, 2016; Cox *et al*., 2017; White *et al*., 2019). Rosenzweig (2003) argues that if human-occupied areas are made to host the maximum number of urban adapters and urban exploiters, then management of natural reserves can focus on urban avoiders for maximal conservation value.

A large part of the work of reconciliation ecology lies in identifying *habitat analogs* and managing developed areas to increase the effectiveness of these analogs (Eversham *et al*. 1996, Lundholm & Richardson 2010, MacIvor & Ksiazek 2015). A commonly cited example of a habitat analog is apartment building ledges acting as analogs for the rock outcrop and cliff habitats of *Columba livia* (common pigeon) and *Falco peregrinus* (peregrine falcon) (Lundholm & Richardson 2010). There are numerous examples of effective habitat analogs throughout the world, but the evidence so far shows that they currently support only a small number of species (Lundholm & Richardson 2010). Management can increase the effectiveness of existing habitat analogs, but reconciliation on the scale that is needed to combat biodiversity loss requires the creation of new artificial habitat analogs (Rosenzweig 2003). This approach shares in the artistic vision and ecological aims of habitat sculpture and so will yield relevant research.

2.1.3 Artificial Habitat Structures

Habitat structures are physical features of the environment that organisms utilize for various functions including shelter, hunting, communication, and reproduction. Coral reefs are a noted habitat structure in the marine environment that host an incredible diversity of life. In the terrestrial environment, trees (both living and dead), rocks, and soil are where most habitat structures are found. Trees and other woody vegetation host many different habitat structures used by many different organisms. This is especially true of standing dead trees known as *snags*, and large old trees known as *veteran trees* or *habitat trees* (Le Roux *et al*., 2014; Horák, 2018). Kraus *et al*. (2016) list 16 habitat structures found on trees including woodpecker holes used by cavity nesters, gaps underneath bark used by bats and invertebrates, and crevices utilized by mosses and lichens (Kraus *et al*., 2016). Rocks can provide crevices used as refuge by a wide variety of organisms that can exploit their microclimatic properties, such as reptiles and amphibians (Croak *et al*., 2010; Lelièvre *et* al., 2010; Morris *et al*., 2016).

A habitat structure can be necessary for an organism's survival, but it is usually not sufficient without other elements of its habitat. *Habitat* is a more encompassing term that refers to a range of objects, conditions, and environments that an organism needs to survive (Morris *et al*., 2016; Thomas, 2019). For instance, A flat rock with certain thermal properties is an important habitat structure used for basking by the Australian broad-headed snake (*Hoplocephalus bungaroides*), but its habitat also includes the landscape that it travels through, its prey, its water sources, and possibly other habitat structures (Westrich, 1996; Croak *et al*., 2010). *Ecological niche* is a concept related to habitat, but that also includes behavioral interactions between organisms, their environment, and other organisms (Grinnell, 1917). For instance, two organisms may occupy the exact same habitat, but if one comes out to feed in the morning, and the other feeds at night, then they occupy different ecological niches. This division of habitat between organisms is called *niche partitioning* (MacArthur, 1958). In addition to providing habitat structures in the form of sculptures, general habitat requirements and niche dynamics of target organisms and communities must be considered in habitat sculpture installations if they are to be successful.

When there are not enough of habitat structures in the environment to meet the needs of an organism or population, they become *limiting factors*. For instance, the eastern bluebird (*Sialia sialis*) uses hollow cavities in dead wood as a habitat structure for nesting and raising its young. Because humans tend to eliminate the dead and dying trees that host these cavities, and because the small number of cavities that still exist are taken by more aggressive birds, the number of bluebirds in eastern North America is *limited* by the number of available cavities (Newton, 1994). Once this limiting factor is eliminated by providing an abundance of artificial nest boxes, the population of bluebirds increases (Sauer & Droege, 1990; Kight & Swaddle, 2007). When nesting cavities cease to be the limiting factor, another factor such as the amount of food, access to water, competition, or predation becomes the predominant limiting factor. The amount of food in an area is the most common limiting factor for wild populations, but in many cases habitat structures are clearly demonstrated to be primary limiting factors (Newton, 1994; Brady *et al*., 2000; Holloway *et al*., 2007).

In human-dominated landscapes, habitat structures tend to become limiting factors because they are often destroyed to make way for agriculture, housing, and other infrastructure (Lundholm & Richardson, 2010; Niemelä *et al*., 2011). In these areas, artificial habitat structures can be created to sustain wild populations (Cowan *et al*., 2021; Watchorn *et al.*, 2022). They can be used as either short term stop gaps until natural structures can be replenished, or as permanent replacements in human-occupied areas like dense urban centers that can't host natural structures (Lindenmayer *et* al., 2012; Le Roux *et* al., 2014; Micó, 2018).

Artificial habitat structures have been created throughout history for a variety of motivations, but recently interest has grown in using these structures for conservation purposes (Cowan *et al*., 2021; Watchorn *et al.*, 2022). Many studies in recent years have made comparisons between artificial habitat structures and their natural analogs to improve their functionality for conservation (Grüebler *et* al., 2014; MacIvor & Packer, 2015; Maziarz *et al*., 2017). By looking to natural as well as artificial habitat structures, many possibilities for habitat sculpture are brought to light. This is especially true for natural habitat structures that do not have a long history of research and artificial replication (e.g., insect leaf rolls, water-filled tree holes). Replication of structures like these holds promise for innovation and discovery.

2.2 ECOLOGICAL DESIGN AND ECOLOGICAL ENGINEERING

Ecological engineering can refer to a wide variety of practices from the wholesale creation of new landscapes and ecosystems to the construction of small objects that serve some ecological or environmental function (Figure 3; Mitsch & Jørgensen, 2004; Cordell, 2012; Loke *et* al., 2015; Chapman *et al*., 2018). Ecological engineering of small structures, also called *green infrastructure* or *blue infrastructure*, is of more relevance to habitat sculpture because of the similarity in scale. Ecologically engineered structures are typically existing pieces of infrastructure that modified to create habitat for specific species or communities, while still letting the structures serve their original purposes (Naylor *et* al., 2017; Chapman *et al*. 2018; O'Shaughnessy *et al*., 2020). Research done in this area is highly relevant to habitat sculpture because many methods of habitat creation have been implemented and tested in a variety of settings (Naylor *et* al., 2017). Unfortunately, most artificial habitat creation efforts in this field are focused exclusively on the marine environment (Cereghino *et al*., 2012; O'Shaughnessy *et al*., 2020). Since this thesis is focused on the terrestrial environment, research from this field is somewhat limited.

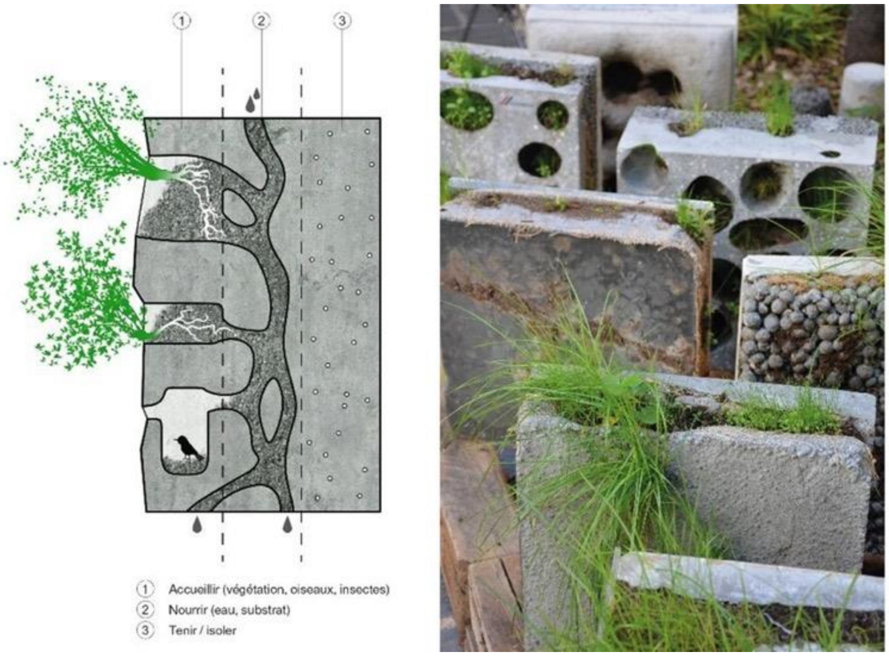

Figure 3. Biomimetic façade system. Source: Chayaamor-Heil & Vitalis (2021). Images from ChartierDalix architects.

While nature has always inspired architectural design, contemporary ecological design approaches in architecture go beyond inspiration by including actual natural systems and living organisms (Figure 3; Montàs & Chayaamor-Heil, 2018; Catalano *et al*., 2021). This is achieved most often in practice through the inclusion of vegetation in the form of green roofs, living walls, and site landscaping (Catalano *et al*., 2021; MacKinnon *et* al., 2021). These approaches often focus on the benefits to humans (e.g., reduced temperature, decreased pollution, water filtration, psychological benefits, etc.) rather than benefits to non-human organisms and communities (Catalano *et al*., 2021). *Biomimetic architecture* is an emerging branch of ecological design that seeks to reproduce biological and ecological functions within architectural designs (Aldersey-Williams, 2004; MacKinnon *et* al., 2021; Chayaamor-Heil & Vitalis, 2021). This approach goes beyond merely applying vegetation and habitat features to pre-conceived designs, and instead allows biology and ecology to shape the designs of buildings (Chayaamor-Heil & Vitalis, 2021; Vitalis & Chayaamor-Heil, 2022). The thorough integration of ecological functionality with human functionality in biomimetic architecture are highly relevant to the habitat sculpture approach.

The design fields discussed above overlap with fine art in many ways so that the boundaries often become blurry. Design includes visual aesthetics and artistic considerations but exists primarily to serve practical functions and solve problems. Likewise, fine art can have practical functions, but is primarily concerned with exploring emotions and ideas that are meant to affect viewers. Habitat sculpture, along with other ecological art approaches, finds itself somewhere between art and design because its functional aims are integral to its visual and conceptual artistic aims. Because ecological design and ecological engineering are fields that address the same environmental issues as ecological art (climate change, biodiversity loss, etc.), the tools and techniques they use are highly relevant to habitat sculpture (Palazzo & Steiner, 2012; Chapman *et al*., 2018).

2.3 ECOLOGICAL ART

Artists in the *ecological art* or *eco-art* movement are taking part in the effort to tackle sociocultural factors that drive species loss and habitat destruction by making bold artistic statements and interventions (Spaid, 2002; Schoenacher, 2013). These works stimulate dialogue and awareness around environmental issues, often while directly engaging with surrounding ecosystems (Geffen *et al*., 2022). Some practitioners focus on raising public awareness of environmental issues through art, some use natural materials and phenomena to create their work, and some collaborate with scientists and activists to restore degraded ecosystems (Bower, 2010; Kagan, 2015). All these diverse practices are united by a shared set of principles and motivations that include respect for natural ecosystems and the desire to encourage long-term flourishing of the social and natural environments in which we live (EcoArt Network, 2016).

Ecological art is related to the land art movement of the 1960's, and to the social political protest art of the same era (Kagan, 2015). In the 1990's, the term ecological art came into use to differentiate the movement from other kinds of art which use natural materials and address environmental issues, but do not directly engage with ecosystems in beneficial ways (Kagan, 2015). One of the first widely known and publicized works of modern ecological art was American artist Mel Chin's 1991 piece, *Revival Field*. In *Revival Field* (Figure 4), Chin collaborated with a scientist named Dr. Rufus Chaney to plant hyperaccumulating plants[1] that would extract metals from the soil to restore the ecological community that no longer existed on the site (Art21, 2004). By removing toxins from the soil, Chin conceptualized the piece as metaphorically sculpting the ecosystem in the same way that a marble sculpture is made by removing pieces of stone, 'sculpting' a polluted ecosystem into a healthy one (Art21, 2004). The idea that an art piece could have tangible, physical effects on the environment, and that those physical effects could become a part of the conceptual beauty of the piece, is an idea that has inspired many ecological artists over the years, including myself.

Habitat is often created in ecological art projects by artists who collaborate with restoration specialists or landscape designers (Spaid, 2002). These projects are usually created on large landscape scales (i.e., parks, wilderness areas), or they take the form of widespread conceptual interventions such as Joseph Beuys 1982 piece *7000 Oaks*, in which they planted 7000 oak trees in Kessel, Germany. Creating habitat through individual sculptures presents very different opportunities and challenges, both artistically and ecologically.

Figure 4. 'Revival Field' by Mel Chin, 1991. Source: Art21, 2004.

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[1] Hyperaccumulators are plants that can grow on metalliferous soils and accumulate heavy metals and other toxins in their organs without suffering phytotoxic effects (Rascio & Navari-Izzo, 2011).

Figure 5. (left) 'Crossing the Rubicon' by Jason deCaires Taylor, 2012; (right) 'Nexus' by Jason deCaires Taylor, 2009. Source: (Taylor, 2020).

Perhaps the best-known examples of sculptures that provide habitat in their physical form are artificial reef sculptures pioneered by British sculptor Jason deCaires Taylor (Figure 5). These sculptures are made from a type of concrete that is specially formulated to have the correct pH for coral growth (Taylor, 2020; ECOncrete, 2022). The surface texture and orientation of the sculptures also accommodate the growth of coral. Spawning corals and other free-floating organisms latch on to the sculptures and grow until they form a new reef in previously barren stretches of ocean floor. Of more relevance to my research are pieces with similar modes of action that have been made in the terrestrial environment by artists like Mark Dion, Lynne Hull, and Jackie Brookner.

Mark Dion is an American conceptual artist who explores the roles of science and knowledge in society through his artwork (Marsh, 2009). One of his best-known pieces is his 2006 mixed media installation *Neukom Vivarium* (Figure 6). For this piece, Dion took a 60-foot downed Western hemlock (*Tsuga heterophylla*) from a forest outside Seattle, Washington, and constructed a high-tech greenhouse to sustain the life growing on the dead wood (Art21, 2006). It is installed at the Olympic Sculpture Park in Seattle. Visitors are given magnifying glasses to closely inspect the fungi, insects, lichens, and plants living there. The greenhouse is incredibly expensive and labor intensive to run, which is the central concept of the piece. Dion wanted to show that it takes all this money and technology to keep this living system functioning, when nature can do a much better job for free if we just leave it on the forest floor (Art21, 2006). The creation of habitat space is integral to the artistic concept of this piece, much like what I am trying to accomplish with my artificial habitat sculptures. The difference lies in the fact that I am trying to create habitat that is integrated into its environment, whereas this piece is cut off from the surrounding ecosystem. This reflects the different conceptual goals being pursued.

Figure 6. 'Neukom Vivarium' by Mark Dion, 2006. Source: (Art21, 2006).

Figure 7. (left) 'Habitat' by David Nash, 2015; (right) 'Wooden Boulder' by David Nash, 1978 Sources: (left) https://warwick.ac.uk/services/art/artist/davidnash/wu1000; (right) http://ntwelshcoast.blogspot.com/2013/11/the-rediscovered-boulder.html

David Nash is a British sculptor who has been creating sculptures with wood, living trees, and the natural environment since the 1960s (Andrews, 1999). They have made many pieces that fall under the category of ecological art, such as his acclaimed 1978 piece *Wooden Boulder*, in which a giant wooden sphere was left in a forest in North Wales to periodically roll through the landscape on its own accord for several decades. It was last seen floating in an estuary in 2015 (Gayford, 2019). One of his recent pieces uses the concept of artificial habitat. In 2015, the University of Warwick in Coventry, England, commissioned Nash to make a sculpture using a 21-foot-tall cedar that had fallen in a storm (Buxton, 2016). The piece is titled *Habitat*, and has holes and slits cut into it, while largely maintaining the structure of the cedar tree (Figure 7). Nash states that, "The sculpture will change over the years, becoming part of the wood's eco-system as it weathers and creatures inhabit it," (Buxton, 2016).

Lynne Hull is a sculptor and ecological artist who describes their work as trans-species art (Preece, 2011). They say of their work "My sculptures and installations provide shelter, food, water or space for wildlife, as eco-atonement for their loss of habitat to human encroachment," (Wead.org, 2020). Hull's work accomplishes this by creating sculptures that act as bird perches, floating rafts, and basins for water (Figure 8). This concept is very similar to what I am researching in that it uses sculpture to interact with the physical ecosystem while remaining an aesthetic object to the human viewer. The main difference between Hull's work and mine is the setting. Hull locates their pieces in degraded environments that are sparsely inhabited by people, whereas my work is set in populated areas like cities and towns (Preece, 2011). There are clear advantages to working in this setting since animals are more likely to interact with the sculptures if there aren't people around to scare disturb them.

Figure 8. (left) 'Reservoir Tree' by Lynne Hull, 1994; (right) 'Duck Island' by Lynne Hull, 1998. Source: https://www.artdesigncafe.com/lynne-hull-art-interview

Jackie Brookner was an ecological artist and designer who created work collaboratively with scientists, engineers, and restoration specialists (Gould, 2015). They created sculptures that provide ecological benefits by filtering water, providing growing mediums for mosses, and drawing attention to ecological processes like water filtration (Pujol, 2013). They called these works *Biosculptures*, and often integrated them in larger restoration projects such as the Dreher Park restoration project in West Palm Beach, Florida (Figure 9). Brookner defined

Biosculptures as “…living sculptures that use the capacity of carefully chosen plants to clean and filter water. Made of mosses, ferns and other plants growing on stone and concrete structures, they provide ecological and aesthetic solutions to water quality and water quantity problems.” The habitat sculpture approach I am developing uses many of the same methods as Brookner’s work but focuses more on habitat structures than ecological processes.

Figure 9. (left): ‘The Gift of Water’ by Jackie Brookner, 2001; (right): ‘Dreher Park Biosculptures’ by Jackie Brookner, 2004. Source: http://jackiebrookner.com/project/biosculptures/

Figure 10. ‘Dwelling: Shenandoah Valley’ by Sarah Preebles, 2019. Source: Preebles, 2019.

Sarah Preebles is an ecological artist making large sculptural earthworks for native bees. Their *Dwelling* series combines native bee habitat with multisensory experiences that educate viewers about native bees and pollinators (Preebles, 2019). Viewers can watch bees tunnel behind plexiglass sheets and listen to an amplified transmission of them digging through headphones. In their 2019 piece ‘Dwelling: Shenandoah Valley’, a large curving wall made of clay-rich earth provides sites for ground nesting bees to tunnel into (Preebles, 2019). Preebles collaborated with Lisa Kuder, a doctoral student at The University of Maryland’s entomology department to create this habitat structure. There are many cavity-nesting structures for bees that are artistically made, but this project goes beyond simply decorating an existing artificial habitat structure and creates something new that has synergistic interactions between the form, the artistic concept, and the function. My work seeks to create these same kinds of synergistic interactions, but targeting multi-species assemblages that may or may not include structures for bees.

Figure 11. ‘Sentinel Offering Kernos: Woodcock, Oysters, Lichen’ by Rachel Frank, 2021. Source: Frank, 2021.

Rachel Frank is a contemporary artist working with ceramics and other media. Their 2021 piece ‘Sentinel Offering Kernos: Woodcock, Oysters, Lichen′ incorporates habitat structures such as basins and hollow cavities, as well as native plant resources for pollinators (Frank, 2021). *Kernos* are ancient Greek vessels used to give offerings, and in this piece Frank creatively interprets the form to give offerings to native species that are considered indicators of healthy ecosystems. The concept of this sculpture as an offering vessel is enmeshed with its ecological functionality, creating a form where habitat structures are integral parts of the piece rather than seeming like an afterthought. What distinguishes this work from some of the other pieces covered so far, and what I wish to emulate with my habitat sculptures, is the centrality of aesthetics and visual beauty in the form. Some work tends to disregard the visual elements, creating works of art that are more like engineered structures than fine art sculptures. This piece shows that visual beauty, conceptual beauty, and habitat functionality can all work together and benefit each other.

These artists and many others are exploring the concept of sculpture as habitat. Habitat sculptures share many methods and objectives with other ecological art approaches, but their unique attributes require new research and fabrication methods to be developed. My thesis project attempts to do that research and development and will hopefully be useful for sculptors will all kinds of artistic approaches. The aims that differentiate my specific approach to habitat sculpture include i) the focus on ecology in predominantly in human-occupied areas like cities and towns, ii) the aim of providing long-term sustainable habitat that tangibly boosts wild populations, and iii) the focus on creating habitat for ecological assemblages and communities rather than individual species or groups.

3. HOW SCULPTURE INSTALLATIONS CAN CREATE HABITAT

Large outdoor sculptures do not normally contribute habitat resources to their ecological surroundings. Bronze statues, memorials, and abstract sculptures made from stone and steel can be found in almost any populated area, but rarely do these sculptures interact with non-human organisms beyond offering unintentional perches for birds or lattices for spiderwebs. For a sculpture to become an active part of the ecosystem, its physical form must be readily exploitable by wild organisms. This means sculpting with shapes that mimic important habitat structures that exist in nature like tree hollows and rock piles. By understanding how these habitat structures function in nature, sculptors can go beyond superficial resemblances and instead reproduce the functions these structures perform. Other physical properties of sculptures such as material, color, and orientation can be chosen to intentionally to affect the ways that sculptures repel or attract organisms. For example, a statue made entirely of bronze (which is naturally antimicrobial) will be far less hospitable to life than one made of untreated wood. And a sculpture with a nesting cavity facing full sunlight might become too hot for target organisms to comfortably inhabit.

If a sculpture succeeds in attracting non-human organisms, then other elements of the organism's habitat such as access to food, water, and territory must be present if they are to persist and thrive (Westrich, 1996). For example, cavity-nesting bees may find suitable nesting sites in a habitat sculpture, but if the pollen-producing flowers they need to provision their nests are too far away, they can deplete their energy reserves traveling back and forth and die prematurely (MacIvor, 2017). In most cases, habitat structures are only one piece of the puzzle that is an organism's habitat. Additional requirements that cannot be satisfied by a habitat sculpture can be provided in the surrounding site in the form of vegetation, water features, and other added resources. In this way the space surrounding the sculpture becomes part of the piece, creating a sculpture *installation* that can create a more complete habitat than the sculpture could provide on its own. Also covered in this chapter is a method for protecting existing habitat structures and resources using sculpture. Although this method does not create new habitat, it is functionally similar to the other techniques covered.

This chapter can be used as a practical guide for anyone wishing to create habitat sculptures. The forms, properties, and habitat resources discussed here are by no means exhaustive, but they can provide starting points for inspiration and investigation. The methods and techniques described should be customized based on region, target organisms, and ecological objectives.

3.1 PHYSICAL FORMS

At its most elemental level, sculpture is the creation of three-dimensional physical forms. In most types of sculpture, physical forms are made primarily to achieve visual or conceptual artistic effects (Lamarque & Olsen, 2018). In habitat sculpture forms are meant to create visual and conceptual effects for human viewers, but also to recreate the functions of certain habitat structures. Breaking habitat structures down into simple shapes that retain functionality allows sculptors to seamlessly integrate visual aims with functional aims. The most functional forms for habitat sculpture according to my research appear to be i) concave shapes that can shelter and house organisms (or collect debris and water), ii) crevices and other interstitial spaces that can provide shelter and favorable microclimates, iii) spatial levels that split up vertical space into usable layers so organisms can be separated from each other, and iv) surfaces and textures that can serve purposes like reptile basking or bryophyte growth.

Concave forms provide shelter and resources for a wide variety of animals and other life forms. For the purposes of habitat sculptures I will review concavities of varying shapes and sizes. These range from pinhole cavities used by cavity-nesting insects to large tree hollows that could fit a mother bear and her cubs. These hollow shelters can protect organisms from weather conditions such as wind, rain, and harmful temperatures; and from biological threats such as predation, parasitization, and competition (Stokland *et al*., 2012). Many organisms use such concavities to rear their young. Cavities are also used for storage space, as can be seen in many squirrel species who store food in tree hollows (Stokland *et al*., 2012). For small organisms such as arthropods and microbes, these protected pockets can become rich ecosystems in which complex food webs of herbivory and predation all play out in relatively self-contained spaces (Micó, 2018). When oriented in a certain way, concave forms can fill with debris and water, providing a necessary resource for many organisms and a necessary living medium for aquatic organisms in terrestrial environments (Kitching, 2000). In sculptural terms, these are all concave shapes that differ from each other in degree but not in kind.

Interstitial spaces are the spaces between objects, or gaps between objects and the ground. Although like cavities in habitat functionality, interstitial spaces are different in kind rather than degree from other cavities when viewed from a sculpture standpoint. In nature these spaces can be found under exfoliating bark, in rock or stick piles, and in small crevices where plants and other organisms can grow and shelter. Artificial analogues include trash piles, loose siding on buildings, piles of objects like plywood or metal, and spaces around intentionally created artificial habitat structures like artificial rocks. These spaces are home to a distinct set of fauna including bats, amphibians, reptiles, invertebrates, plants, fungi, and microbes.

The next category of relevant forms are *spatial layers*. Structures that contain separate layers in three-dimensional space create more spatial niches for organisms to inhabit, and consequently host more biodiversity (Loke *et al*., 2015; Torres-Pulliza *et al*., 2020). These spatial layers can be platforms that divide up vertical space like ridges on cliff faces or ledges on high-rise buildings. They can also be protrusions like tree branches that create perches separated in three-dimensional space. Concave forms and interstitial spaces focus on negative space in sculptural terms, whereas spatial layers represent positive three-dimensional structures.

The final relevant category of physical forms are *complex surfaces*. The surface rugosity and texture of rocks, tree bark, dead wood, and human-made objects affects their habitat suitability for a variety of organisms. Growth of epiphytic and epilithic plants such as mosses and lichens can be affected by surface rugosity (Lundholm, 2011). Surfaces that are sufficiently complex can also host entire food webs of invertebrates and microbes that shelter and hunt in these miniature landscapes (Lundholm, 2011). Most of the biological research on creating complex artificial surfaces has been conducted in the marine environment (Loke *et al*., 2015; O'Shaughnessy *et al*., 2020). It remains to be seen whether fabrication methods from this research can be successfully applied to terrestrial environments, but habitat sculptures may provide an ideal setting to explore this.

A general principle to guide the physical form of habitat sculpture creation is structural complexity. Complex structures in nature provide greater varieties and densities of niches, thereby supporting higher species abundance and biodiversity (Loke *et al*., 2015; Torres-Pulliza *et al*., 2020). Figure 12 shows how complex sculptural forms will naturally hold more habitat potential than simple forms. This can be seen on a macro scale with cavities, spaces, and layers, and on a micro scale with complex surfaces. This principle of complexity creates a distinct visual aesthetic that I will explore in the sculpture installations I created for this project (section 5).

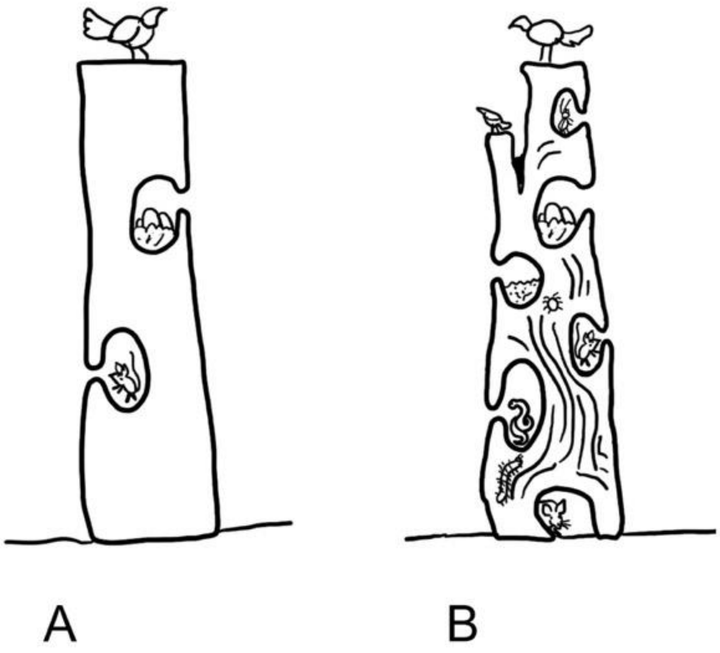

Figure 12. Increasing structural complexity increases available niche spaces. Object A provides 3 possible niches, while object B provides 10. Source: RJH Artworks, 2022.

Size also plays an important role in habitat sculpture. Larger areas and surfaces hold more physical niches, thereby increasing ecological niche space, so increasing size also increases species abundance and diversity (Torres-Pulliza *et al*., 2020). This ecological principle is generally applied on the landscape scale rather than the relatively small scale of sculpture, so it is unclear how relevant it is to habitat sculpture. Since many of the habitat structures that are reviewed in this research are found in trees, it may be beneficial to create works that approach the scale of a tree when possible. Studies of habitat selection among cavity-dwelling organisms often find strong preferences for cavity heights of 4 m and above, likely to avoid predators on the ground (Nielsen *et al*., 2007; Micó *et al*., 2015). While there is often wide variation in these preferences, a larger sculpture will probably host more organisms than a smaller one.

3.1.1 Concave Forms

Large Tree Hollows

Large cavities in trees, or tree hollows, are essential habitat structures for a wide variety of birds, mammals, reptiles, amphibians, and invertebrates (McComb & Lindenmayer, 1999; Stokland *et al*., 2012). In nature, tree hollows are created either from excavation by a primary cavity-nesting bird such as a woodpecker, or through a fungal rot process. Fungal rot occurs when a tree's bark and outer layers are penetrated, most commonly through branch breaks, and the tree cannot immediately heal the damage. After the fungi invade, other organisms like insects and bacteria help widen this hole into a cavity, creating a characteristic form where the interior diameter of the cavity is larger than the diameter of the entrance hole (Stokland *et al*., 2012). This form provides ideal shelter and buffering inside the cavity from outside conditions (Mainwaring, 2011). Wood rotting fungi and other xylotrophic[2] organisms are constantly eating away at the walls of tree hollows so that their form is constantly changing and expanding over time (Carlsson *et al*., 2016). Cavities in wood provide benefits including thermal insulation and protection from predation and parasites. Conversely, there can be drawbacks when predators and parasites use tree cavities to corner their prey or host (Stokland *et al*., 2012).

Tree hollows with entrances at least 2 cm wide and cavities at least 20 cm deep are essential for many forest vertebrates and certain specialized insect communities (McComb & Lindenmayer, 1999; Bergman *et al*., 2012). Smaller tree cavities entrance diameters under 2 cm are primarily the result of wood-boring insects, and will be discussed separately as they are physically and functionally much different than large tree hollows (see *Small Cavities* below). The diameter of the entrance hole and the interior dimensions of the hollow are the primary determinants of which organisms will use them (McComb & Lindenmayer, 1999; Le Roux *et al*., 2016). These dimensions should therefore be carefully considered and designed in habitat sculptures by consulting scientific literature and other sources.

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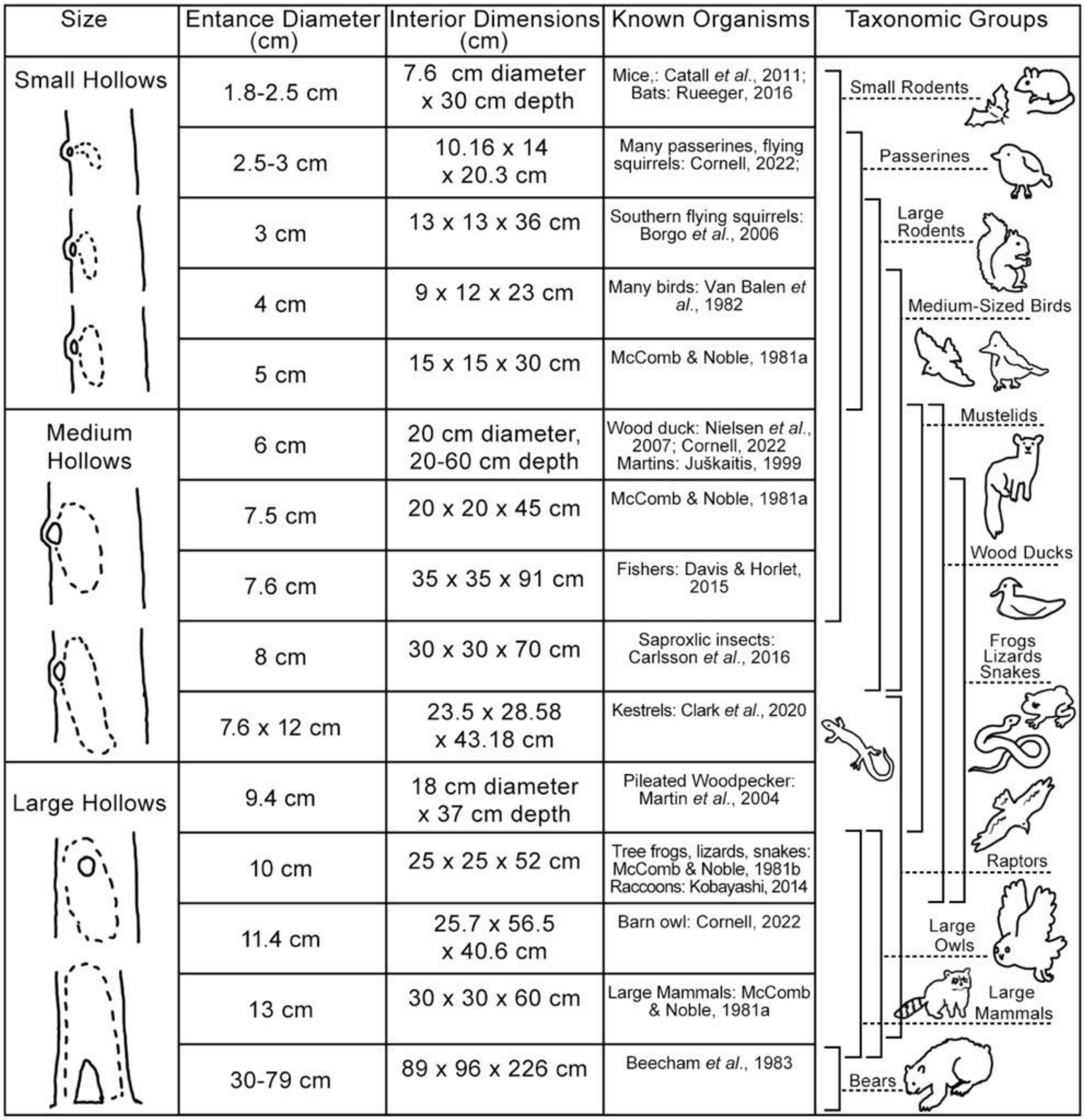
[2] Meaning organisms that feed on wood (Stokland *et al*. 2012).



Size	Entance Diameter (cm)	Interior Dimensions (cm)	Known Organisms	Taxonomic Groups
Small Hollows	1.8-2.5 cm	7.6 cm diameter x 30 cm depth	Mice,: Catall *et al.*, 2011; Bats: Rueeger, 2016	Small Rodents
	2.5-3 cm	10.16 x 14 x 20.3 cm	Many passerines, flying squirrels: Cornell, 2022;	Passerines
	3 cm	13 x 13 x 36 cm	Southern flying squirrels: Borgo *et al.*, 2006	Large Rodents
	4 cm	9 x 12 x 23 cm	Many birds: Van Balen *et al.*, 1982	Medium-Sized Birds
	5 cm	15 x 15 x 30 cm	McComb & Noble, 1981a	
Medium Hollows	6 cm	20 cm diameter, 20-60 cm depth	Wood duck: Nielsen *et al.*, 2007; Cornell, 2022 Martins: Juškaitis, 1999	Mustelids
	7.5 cm	20 x 20 x 45 cm	McComb & Noble, 1981a	
	7.6 cm	35 x 35 x 91 cm	Fishers: Davis & Horlet, 2015	Wood Ducks
	8 cm	30 x 30 x 70 cm	Saproxlic insects: Carlsson *et al.*, 2016	Frogs Lizards Snakes
	7.6 x 12 cm	23.5 x 28.58 x 43.18 cm	Kestrels: Clark *et al.*, 2020	
Large Hollows	9.4 cm	18 cm diameter x 37 cm depth	Pileated Woodpecker: Martin *et al.*, 2004	
	10 cm	25 x 25 x 52 cm	Tree frogs, lizards, snakes: McComb & Noble, 1981b Raccoons: Kobayashi, 2014	Raptors
	11.4 cm	25.7 x 56.5 x 40.6 cm	Barn owl: Cornell, 2022	Large Owls
	13 cm	30 x 30 x 60 cm	Large Mammals: McComb & Noble, 1981a	Large Mammals
	30-79 cm	89 x 96 x 226 cm	Beecham *et al.*, 1983	Bears

Table 1. Natural and artificial cavities sizes that are known to host various organisms.

The preferred entrance hole size and cavity dimensions for many species are detailed in the scientific literature on tree hollows and nest boxes (McComb & Noble, 1981a). Table 1 gives a rough outline of which taxonomic groups are known to inhabit which size hollow. A more detailed list of hollow-dwelling species in the northeastern USA and their preferred cavity dimensions is given in section 3.6. Body size typically dictates the cavity dimensions organisms prefer (Beecham *et al*., 1983; Le Roux *et al*., 2016). An entrance hole that fits an organism's own body size means that the cavity is safe from larger predators and competitors (Zingg *et al*., 2010). The entrance hole must of course be large enough to allow an organism access if they are to use the cavity. Preferred interior dimensions are also closely tied to body size, with most species preferring a snug fit (Martin *et al.*, 2004). Sawyer (1969) shows that cavities whose interior dimensions are too large cause birds to waste valuable time and energy filling the cavity with nesting material until a snug fit is achieved. At the same time, cavities should be shaped in such a way that the inhabitant is not directly exposed to outside conditions. The distance between the entrance hole and bottom of the cavity is called the *danger distance* (Mazgajski & Rykowska, 2008). The danger distance should be great enough so that nesting organisms are protected from inclement weather and can escape the prying claws and beaks of predators.

Although many organisms show preferences for cavities that closely match their body size, small organisms are often found in larger cavities as well (McComb & Noble, 1981a). This means that while a small cavity can host only small animals, a large cavity can host small, medium, and large bodied animals. There may therefore be higher species diversity associated with larger hollows (Micó *et al*., 2015; Le Roux *et al*., 2016). Because small animals who inhabit large hollows may experience a higher rate of predation, the best approach for habitat sculptures might be to provide multiple hollow sizes while prioritizing larger hollows in general.

Most organisms seem to prefer cavities with a single entrance hole, seemingly because they can be more easily defended. There are exceptions to this tendency such as the European little owl (*Athene noctua*), which prefers long cavities with multiple branches and entrances (Schönn, 1986). Bock (2011) postulates multiple reasons that *A. noctua* might show this preference. It could be because cavities with multiple entrance holes happen to be larger, the long winding cavities may provide a variety of thermal environments for the owls to choose from, or the multiple entrance holes allow for owls to escape attack by a predator. These more structurally complex hollows may be of more interest to sculptors than simple tree hollow forms, but this must be weighed against the risks of increased predation in certain cases.

Aside from the physical form of tree hollows, many other external factors affect species site preferences and nesting success. Studies have found the most important factors to be thermal conditions, orientation, sun exposure, wind exposure, height of the cavity above the ground, and surrounding site conditions such as tree species makeup (Wolf & Walsberg 1996; Ellis, 2016; Zhang *et al*., 2021). Some creatures also have preferences relating to whether hollows are in living trees, or in standing dead trees known as *snags*.

Nest Boxes and Artificial Tree Hollows

Virtually all birdhouses and nest boxes are imitations of large tree hollows. Nest boxes are generally successful at attracting and housing certain species, but unique problems can arise from differences between natural tree hollows and these artificial imitations. Differences in temperature, humidity, and durability have all been documented in the scientific literature to cause problems for wildlife (Coombs *et* al., 2010; Grüebler *et* al., 2014; Maziarz *et al*., 2017).

There may also be unintended effects on ecosystems when some species readily adopt nest boxes while other species do not (Lindenmayer *et al*., 2017). Maziarz *et al.* (2017) found that humidity levels were much higher in the natural tree cavities than in artificial nest boxes. It might be assumed that artificial nest boxes are superior in this regard, since high humidity can be associated with parasites, fungi, and other pathogens. But the authors argue that the higher humidity levels in natural tree hollows allows microorganisms to actively break down waste and other debris, thereby reducing parasite and pathogen load. They also found that natural tree cavities provide a larger range of humidity levels than nest boxes. Having a diversity of humidity levels may be beneficial because it allows organisms to choose the microclimates they are best suited for. This leads to the broader point that natural tree cavities offer a much greater diversity of microclimates.

Wall thickness and overall mass are important factors affecting the ecological performance of tree hollows analogs like nest boxes. Thicker walls and more mass around hollows stabilize the temperature inside the cavity. Thermal insulation is a crucial factor for cavity nesting animals, primarily because it protects young offspring who cannot thermoregulate on their own (Maziarz *et al*., 2017). Thermal insulation is also crucially important to ectothermic cavity nesters who cannot regulate their own body temperature (Stokland et al., 2012). Many studies have measured the temperature regimes in artificial nest boxes of varying designs and compared them to natural tree hollows (Grüebler *et al*., 2014). Nest boxes universally have more erratic fluctuations in temperature compared with natural hollows owing to the thin plywood walls of nest boxes (Grüebler *et al*., 2014). Sculptures that add thermal mass more closely resembling the walls of a tree hollow may improve thermal stability and create more favorable conditions.

Researchers and conservationists in recent years have begun testing alternative tree hollow analogs to address the deficiencies inherent in nest boxes. These alternatives include artificial hollows carved into live trees using chainsaws, 3D printed hollows based on scans of natural tree hollows, and other techniques that could be relevant to habitat sculpture (Figure 13). Another nest box alternative that has been used for many decades is artificial log hollows, which are essentially segments of a tree trunk that have been cut in half and had cavities carved into their centers (Sawyer, 1969). Rueegger (2017) and Bengtsson & Wheater (2021) found that chainsaw hollows carved into live trees were readily occupied by a variety of cavity-dwelling organisms in Australia and Germany respectively. Griffiths *et al.* (2018) found that chainsaw hollows mimicked the temperature regimes and microclimates of natural tree hollows much better than either nest boxes or artificial log hollows. This method is highly relevant because chainsaws are frequently used by sculptors working in wood, and the technique itself is akin to sculpting. Innovative 3D printing techniques developed by Parker *et al.* (2022) hold promise for artificial habitat creation efforts, and for habitat sculpture (Watchorn, 2022). These researchers used 3D design software to create artificial hollows that closely resemble the structural complexity of natural hollows. Their reproducible framework allows these structures to be easily modified and produced worldwide. Sculptors and other fine artists are increasingly incorporating new fabrication methods such as 3D printing, creating exciting possibilities for incorporating techniques such as this one.

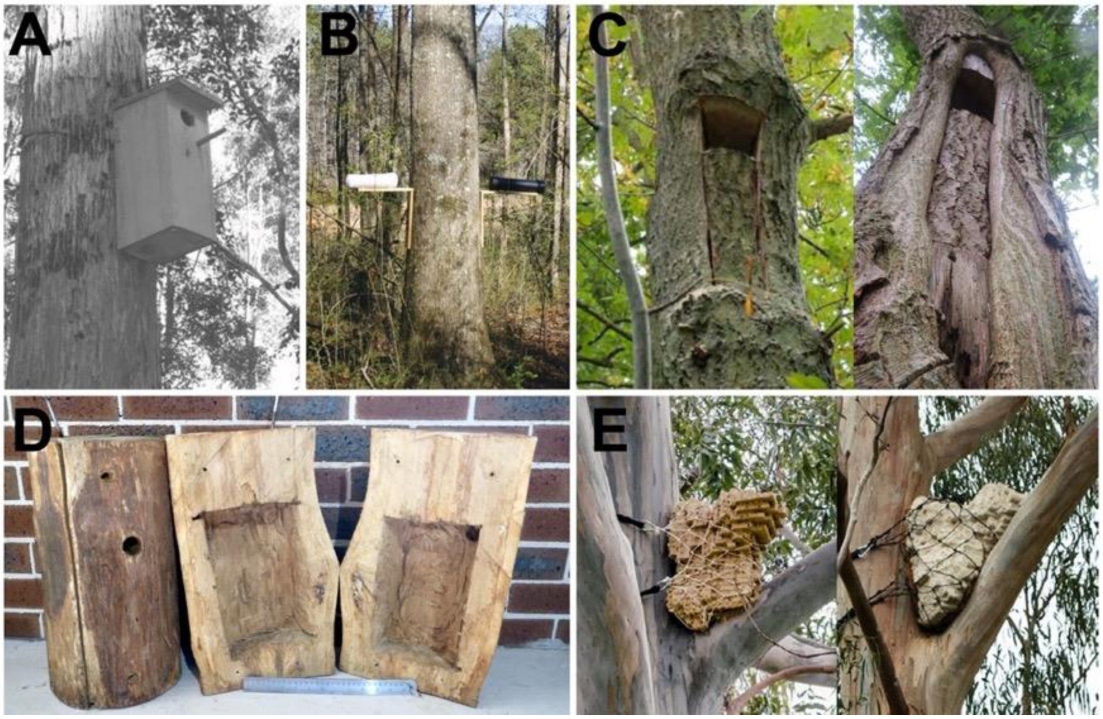


Figure 13. Various artificial tree hollows. A) traditional nest box, B) nest tube for small mammals, C) chainsaw hollow in live tree, D) artificial log hollow, E) 3D printed nesting cavity. Sources: A) Goldingay & Stevens, 2009; B) Catall et al., 2011; C) Bengtsson & Wheater, 2021; D) Griffiths et al., 2018; E) Parker et al., 2022.

Despite their limitations, nest boxes and other artificial analogs of tree hollows have provided opportunities to test cavity size preferences and other variables for numerous species, making them a valuable resource for habitat sculpture. The Cornell Lab of Ornithology provides evidence-backed nest box dimensions targeting dozens of bird species in North America (Cornell 2022). Unfortunately, nest boxes have traditionally been focused on birds and bats to the exclusion of many other cavity dwelling organisms (Cowan *et al*., 2021). Because habitat sculptures are concerned with benefiting ecological assemblages and communities rather than individuals, habitat sculpture practitioners cannot exclusively rely on readily available consumer designs such as those provided by Cornell. For other cavity-inhabiting groups such as rodents, mustelids, large mammals, reptiles, amphibians, and invertebrates, information can be tracked down in the scientific literature on artificial habitat structures. Cowan *et al.* (2021) provides a list of 224 studies covering terrestrial artificial refuges for vertebrate species across the globe, and Watchorn *et al.* (2022) provides sources for a wider range of artificial habitat structures.

Working with the size and shape limitations of organisms may be challenging for some sculptors depending on how they react to creative constraints. Those who respond well to limitations might have no problems working around predetermined hollow dimensions, while others may need to explore different approaches for introducing these habitat structures into the creative process. It should be noted that hollow-dwelling organisms reside in a range of hollow shapes and sizes, and that the dimensions given in the scientific literature are not exact specifications (Table 1). Starting with the rough size and shape of a certain hollow and developing a sculpture from there may result in a sculpture that integrates habitat in a more synergistic way than adding habitat structures at the end. In their articles on biomimetic architecture, Vitalis & Chayaamor-Heil (2022) state that creating an architectural design then adding biological elements to its surface as an afterthought misses the potential of combining biology and art. Their criteria for biomimetic architecture states that biology must inform the design process (Chayaamor-Heil & Vitalis, 2021). From my experience creating habitat sculptures, I feel that there is a similar dynamic at play. It has taken a lot of practice and failed attempts to integrate habitat structures with my intuitive artistic process.

Wood Mould-Filled Hollows

Although vertebrates such as birds and mammals are the most conspicuous users of large tree hollows, when these cavities fill with organic debris (e.g., fallen leaves, decomposed wood, animal droppings, insect frass, etc.), they become habitats for a wide variety of hollow-dwelling invertebrates. Worldwide, over 800 species of insect have been identified in tree hollows so far, with the true number of species likely being much greater (Micó, 2018). Some of these organisms are tree hollow specialists that can exist in no other microhabitat and are among the most threatened species on the planet (Micó, 2018). Vertebrates and hollow-dwelling insects often co-exist in commensal relationships where insects feed on the excrement and nesting material of vertebrates (Ratajc *et al*., 2018; Bock, 2018). Over time the organic debris described above mixes with wood particles from xylotrophic organisms digesting the cavity walls, creating a substance called *wood mould* (Micó, *et al*., 2015). This material is rich in microbial life and nutrients, attracting invertebrate assemblages that change over time as the wood mould ages (Micó, 2018).

Just as with other large tree hollows, mould-filled hollows are being destroyed by human activities. These activities include forestry, agriculture, and cultural practices that do not value the veteran trees and snags that host mould-filled hollows (Lindenmayer *et al*., 2017). Even if we acted now to adequately protect these essential microhabitats, they would not regenerate in time to save the current biodiversity of hollow-dwelling invertebrates (Micó *et al*., 2015). Importantly for habitat sculpture, researchers have begun developing artificial wood mould-filled hollows for conservation purposes (Birtele, 2003; Carlsson *et al*., 2016). Artificial mould-filled hollows can act as a temporary habitat to sustain wood mould communities until natural habitat structures can be regenerated (Smith, 2018). These structures can also act as spatial bridges to connect habitat patches where natural tree hollows remain intact (Jansson *et al*., 2009). Since most tree species take 150 to 300 years to generate cavities large enough for hollow-dwelling invertebrates, artificial mould-filled hollows may be vitally necessary if we want to save these communities from extinction (Jansson *et al*., 2009). The artificial mould hollows currently being researched show high rates of success in attracting and sustaining abundant and diverse species assemblages, including some rare and threatened species (Hilszczański *et al*., 2014). While differences between natural and artificial mould hollows are still being studied, the technique appears promising (Smith, 2018).

Artificial wood mould-filled hollows were developed in a series of studies by Jansson *et al.* (2009), Hilszczański *et al.* (2014), and Carlsson *et al.* (2016). From the outside these structures look like traditional wooden nest boxes, but inside they are modified to house hollow-dwelling invertebrates (Figure 14). The boxes in these studies are made of oak timber (*Quercus robur)* to resemble the temperature and moisture conditions in natural oak hollows. The walls and roof are 2.5 cm thick, and the floor is 5 cm thick to prevent the contents from spilling out after decomposition and wood boring by beetle larvae. Exterior dimensions are 70 cm x 30 cm x 30 cm, with an internal volume of approximately 60 L. The entrance hole is 8 cm in diameter and located 3 cm from the top of the box. An 'x' is milled into the roof where four holes allow in rainwater, and the floor is covered by a 5 cm thick clay basin to retain moisture. The box opens from one side where a plexiglass door allows for observation.

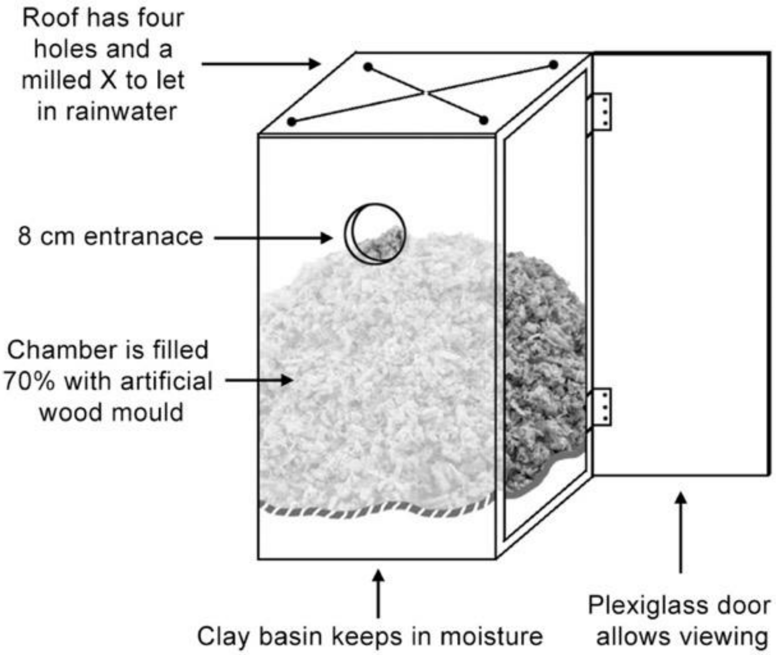


Figure 14. Artificial wood mould-filled hollow from Carlsson et al., 2016. Exterior dimensions are 30 x 30 x 70 cm. Source: image modified from Carlsson et al., 2016.

The key to the success of these structures is the addition of a wood mould-imitating substrate. The boxes are 70% filled with the artificial wood mould, the formulation of which can be customized to target various species and species assemblages. In this series of studies, the wood mould was composed of 60% oak sawdust, 30% oak leaves, and 10% hay. One L of lucerne (*Medicago sativa*) flour and 5 L of water were then added. In the study by Carlsson *et al.* (2016), four additional ingredients were tested to see if they influenced species composition, richness, or abundance. These experimental ingredients were 1) five potatoes, 2) 1 L of oat flakes and one additional liter of lucerne flour, 3) 1 L of chicken dung, and 4) a dead chicken. The potatoes were meant to add moisture, the oat flakes and lucerne flour were meant to add protein, and the chicken dung and chicken carcass were meant to simulate the effects of abandoned bird nests. The dead chicken had significant positive effects on species abundance and richness. The Lucerne flour and oat flakes additive had significant positive effects on endangered *saproxylic*[3] beetle abundance (Carlsson *et al*., 2016).

As with other artificial nest boxes, placement, sun exposure, and other external factors have a significant influence on the success of these structures. In the series of studies by Jansson *et al.* (2009), Hilszczański *et al.* (2014), and Carlsson *et al.* (2016), the boxes were placed 4 m above the ground on the shady sides of oak trees to create stable micro-climates and minimize variation between boxes. Carlsson *et al.* (2016) found that distance from source populations was inversely related to saproxylic species richness. Even so, they found that 70% of saproxylic species present in nearby tree hollows were present in the artificial habitat boxes, even though the boxes were more isolated from source populations.

The authors of these studies point to shortcomings of these structures and recommend improvements be made before deploying them as conservation tools. The exploratory process of sculpture creation may be able to contribute to this development. One alternative method that can be explored through sculpture is the use of salvaged mould-filled hollows. This method was evaluated by Parker *et al.* (2022) for use by vertebrates, and was determined to have several advantages because of similarities in structure and microclimate to intact hollows.

Over the course of this research project, I have started to notice the number of mould-filled hollows that are disposed of in woodchippers and chopped up for low quality firewood. In my travels around coastal Maine and Pennsylvania, I see these habitat structures sitting in lawns and on roadsides awaiting disposal. Salvaging these hollows for use in sculpture may solve certain issues raised by Carlsson *et al.* (2016). The authors state that the amount of wood mould in artificial hollows decreases over time, unlike natural hollows which are constantly adding wood mould as the cavity walls are consumed by fungi and larva. If habitat sculptures use salvaged wood hollows and logs instead of plywood boxes, this natural process of wood mould production would be allowed to occur. Likewise, decomposition of the box floors is a

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[3] Saproxylic refers to species who depend directly or indirectly on dead wood for their survival (Ulyshen, 2018a). Pronounced sap-roe-ZEYE-lic.

major problem for the longevity of these structures that could be solved with a much larger sculptural masses that could be eaten into without mould spilling out. Increasing the size and wall thickness of the boxes to stabilize the internal microclimate is another improvement that the authors suggest which using salvaged hollows would accomplish. Using salvaged mould-filled hollows for conservation purposes or commercial production may be impractical or even detrimental if it was attempted on a large scale. Because sculpture installations are necessarily on a small scale, hollows can be salvaged and used without creating detrimental demand for these scarce natural resources.

Another benefit of using salvaged tree hollows is the natural wood mould they contain. Carlsson *et al.* (2016) found that species composition in the boxes became increasingly specialized over a 10-year period, likely due to the artificial wood mould becoming more like real wood mould as decomposition took place. The authors state that the artificial wood mould mimics the structure of natural wood mould, but not the chemical and biotic characteristics. Using natural wood mould from salvaged hollows, even if the hollow itself cannot be salvaged, may improve the functionality of artificial mould hollows. The orientation of the entrance holes to artificial hollows on habitat sculptures could also be sized and oriented so leaf litter and rain could enter the cavity, replenishing natural sources of wood mould and moisture.

Aside from these practical benefits, the possibilities mould-filled hollows present for habitat sculptures are very exciting. These structures may be better suited to habitat sculptures than vertebrate hollows because invertebrates are less likely to be disturbed by the presence of humans. There is also a unique opportunity to educate viewers about these structures and the communities that inhabit them. The general unpopularity of insects and ignorance of saproxylic invertebrates means that artificial mould-filled boxes are unlikely to become as popular as bird boxes or bat boxes with the public anytime soon. By incorporating them into sculpture installations, there is an implicit message about the value of mould-filled hollows that has an effect beyond explicit communication and education.

Small Cavities

Unlike large tree hollows, cavities in trees that are <1 cm in diameter are typically created by wood-boring insects such as beetles, bees, wasps, ants, flies, and moths. In most of these species it is the larval stage that possess specialized wood-boring capabilities, although adults of some species possess this ability as well (Gimmel & Ferro, 2018). Depending on which species created them, the form of these cavities can be either small tunnels or complex networks of tunnels and chambers called *galleries* (Figure 15). Small cavities of a similar size and shape can also be found in broken stems of woody plants, or in soil where ground nesting insects excavate nests. These cavities are essential habitat structures not only for the creatures that create them, but for a diverse community of organisms that inhabit them during or after their excavation. The inhabitants include fungi, microbes, invertebrates, and even creatures as large as bats (Stokland *et al*., 2012; Gimmel & Ferro, 2018, Gottfried *et al*., 2019). Just as woodpeckers are considered keystone species for large hollow-dwelling creatures, wood-boring insects are considered keystone species for small cavity-nesting communities (Ulyshen, 2016). Fungal and larval decomposition can turn these small cavities into large tree hollows over time, but in general the two types of structures are distinct in size, shape, and species assemblage.

The numerous organisms that inhabit these small cavities are an important food source for many species of woodpecker (*Picidae*) and other charismatic animals such as the American black bear (*Ursus americanus*) (Ferro, 2018, Stokland *et al*., 2012). Analysis of black bear scat has found that up to 58% of their diet consists of carpenter ants (*Camponotus* spp.) during certain times of the year (Noyce *et al*., 1997; Ferro, 2018). Certain wood-boring insects and cavity-dwelling organisms also speed up decomposition of dead wood, freeing up nutrients that are cycled through the entire ecosystem (Stokland *et al*., 2012; Ulyshen, 2016).

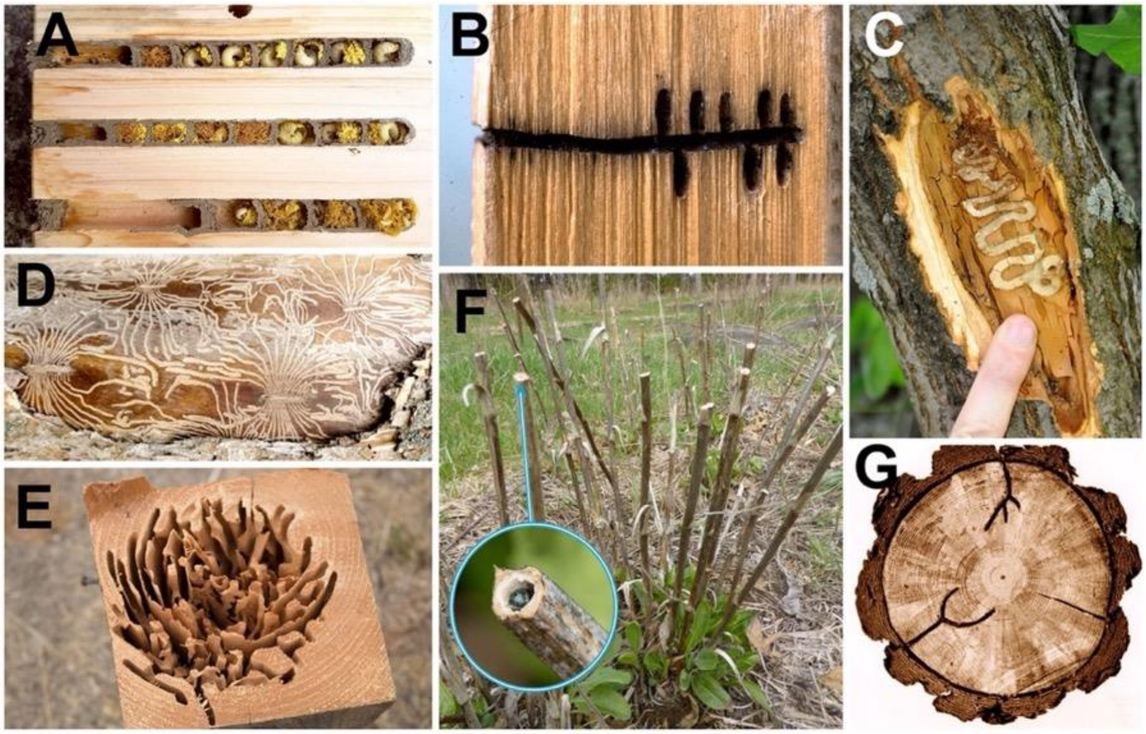

Figure 15. Types of small cavities in trees and woody vegetation. A) Simple tunnel used by cavity-nesting bees and wasps, B) main tunnel with branching cavities for pupal development of Ambrosia beetles, C) winding cavity of a longhorn beetle larva, D) bark beetle galleries on the cambium layer of a tree, E) carpenter ant (Camponotus) gallery, F) small cavities in stems and woody vegetation, G) branching cavities of a large wood-boring beetle. Sources: A) Lee Dingain, https://twitter.com/LeeDingain; B) Clemson Cooperative Extension, https://hgic.clemson.edu /factsheet/ambrosia-beetles/; C) Purdue Extension, https://extension.entm.purdue.edu/; D) https://www.shutterstock.com/image-photo/traces-pest-on-bark-tree-form-1725043510, E) UNH Extension, https://extension.unh.edu/; F) Xerces Society, https://xerces.org; G) modified from USDA Forest Service, https://www.flickr.com/photos/151887236@N05/38707368711/

Probably the most well-known residents of small cavities are cavity-nesting bees and wasps (Hymenoptera). These insects are for the most part solitary and stingless, unlike honeybees and other social bees and wasps (Rahimi *et al*., 2021). They are important pollinators of flowering plants and agricultural crops owing to their diversity and abundance in the landscape (Dainese *et* al., 2018; McCallum *et al*., 2018). Precipitous population declines of bees worldwide have spurred vigorous conservation efforts (Stubbs & Coverstone, 2015). As part of the effort to support these pollinators the public has been encouraged to take steps such as planting native plants and installing artificial cavity-nests (Bauer *et al*., 2015).

Artificial cavity-nesting structures for bees, sometimes called *bee hotels* or *insect hotels*, are probably the most well-known artificial habitat structures after bird and bat nest boxes. These structures contain anywhere from a few cavities to hundreds of cavities grouped together and sheltered under a roof or in a box (Figure 16; MacIvor, 2017). Cavity-nesting bees and wasps will then use these structures to nest, laying each egg in an isolated cell provisioned with pollen (Figure 15A). Once the cavity has been filled with egg bearing cells, the insect caps the entrance, usually with mud or masticated vegetation. The eggs develop inside the cavities for several weeks or over winter and emerge one by one when they are mature. Insect hotels have been successfully used in agriculture and by research scientists for decades (MacIvor, 2017). The popularity of insect hotels among home gardeners and nature enthusiasts has risen steeply in recent years. Although these structures are highly successful in attracting bees and wasps, research on their usefulness for conservation is murky and points to significant flaws which must be addressed (MacIvor, 2017; Rahimi *et al*., 2021).

Figure 16. Various bee hotels and artificial nest cavities. Source: figure from MacIvor, 2017 (top left photo credit: Stephen Humphreys).

The most serious flaws that researchers have found are invasive species making use of insect hotels, improper design leading to mortality and reproductive failure, and the unnatural density of cavities in these structures leading to increased parasitism and disease spread (MacIvor & Packer, 2015; Geslin *et al*., 2020). MacIvor & Packer (2015) suggest that minimizing the number of non-native plants and maximizing the number of native plants in the vicinity of insect hotels will discourage colonization by invasive species. They also suggest that using more naturalistic three-dimensional forms for these structures may help specialist bees make use of the cavities. Geslin *et al.* (2020) suggest that insect hotels avoid using cavities with diameters over 8 mm to exclude the aggressively invasive bee species *Megachile sculpturalis*. Habitat sculptures may be well suited to explore forms that are more naturalistic than the dimensional lumber surfaces that are typically used. Sufficiently large habitat sculptures may also be able to decrease the density of cavities to ameliorate the risk of parasitism and disease spread. By intentionally minimizing these risks through design, and closely monitoring the sculptures after installation, habitat sculptures should be able to successfully incorporate these structures into their physical form.

Just as with vertebrates in tree hollows, entry hole diameter and cavity size are the primary determinants of which cavities an organism will choose to inhabit (Figure 17). Entry diameter preferences closely follow body size (specifically head width), so that larger organisms such as predators and competitors can be excluded. The stability of the structure is crucial, as any movement can cause the insects to abandon their nests (MacIvor, 2017). Individual cavities are drilled into wood and other porous materials at prescribed distances from each other. Bees and wasps have been observed using glass tubes and other non-porous materials, but these are thought to increase fungal infections and disease (Martins, 2012; MacIvor, 2017). Reeds, stems, and bamboo stalks are often bundled together for use as cavities. Elderberry, raspberry, and blackberry are the most used plants in the USA for these purposes. Wood is generally found to be the most successful material, but research is ongoing (MacIvor, 2017).

Cavity diameters range from 1 mm to 10 mm, and lengths range from 5 cm to 20 cm. Using inappropriate dimensions can have negative effects on egg laying behavior and reproductive success (Seidelmann *et al*., 2016). Gruber *et al.* (2011) found that red mason bees (*Osmia bicornis*) nesting in cavities less than 15 cm in length produced offspring that were predominantly male. Entrance holes should be sheltered and oriented so that they do not let in rain. Several authors state that to sustain populations of cavity-nesting Hymenopterans, nesting cavities must be abundant enough that they are not a limiting factor (Fortel *et al*., 2016; MacIvor, 2017). Authors also point out that the extremely high densities and abundances of cavities in these structures present unnatural conditions that may harm wild populations by spreading disease and parasites (Wcislo, 1996; MacIvor & Packer, 2015). These risks and benefits must be balanced against each other when deciding how many cavities to create in a habitat sculpture, but a safe approach would be to err on the side of less dense groupings.

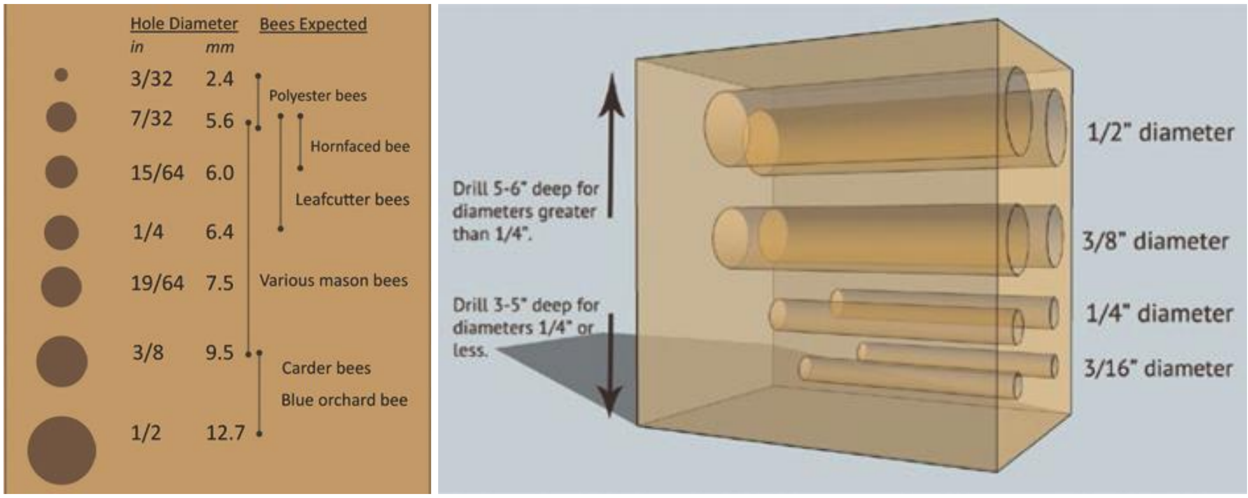

Figure 17. Entrance diameters and cavity lengths for various North American bee taxa. Source: University of Nebraska-Lincoln (Bauer et al., 2015). More information will be given in section 3.6.

Research in North America generally indicates that cavities should be oriented towards the morning sun (pointing southeast) but located in the shade, and oriented away from prevailing winds (Youngsteadt & Favre, 2021). Keeping the entrances free from obstructions such as tall vegetation will help the nesting insects locate the structure and keep track of their individual cavities (Youngsteadt & Favre, 2021). Confusion and disorientation when trying to locate their claimed nests is a known problem in solitary bees and wasps, perhaps because of the unfamiliar structures being used such as dimensional lumber and large bundles of stems (MacIvor & Packer, 2015). Artz *et al.* (2014) found that pattern and color can help bees and wasps recognize their nests when multiple cavities are in close proximity, but Guédot *et al.* (2007) found that excessive patterning caused more disorientation. Artz *et al.* (2014) also found that nest boxes painted light blue hosted more active nests than boxes painted yellow or orange, but these color and pattern preferences are an ongoing area of study (Guédot *et al*., 2007; Rahimi *et al*., 2021). In general, adding texture, color and pattern to these structures appears to be beneficial, which creates many artistic possibilities for visual artists to explore.

A successful artificial cavity-nesting structure should aggregate all the organism's natural nesting conditions and requirements in a relatively compact space. Needed resources around nesting sites include pollen, water, mud, and vegetation. Pollen provides a food resource, and many species use mud and vegetation to create egg cells and plug the entrances to their cavities. Providing nesting sites that do not have these resources nearby can turn these structures into deadly ecological traps (MacIvor, 2017). These additional resources will be discussed further in section 3.3. It should also be noted that most solitary bee and wasp species in North America are ground-nesting, so including bare soil in the landscaping of habitat sculpture installations may be just as beneficial as providing above ground nesting cavities (Code, 2019).

Artificial cavity-nesting structures for bees and wasps have been thoroughly explored in recent years, making for a wealth of information that can be utilized for habitat sculpture (see section 2.3). On the other hand, replication of other small cavities (*e.g.*, Ambrosia beetle galleries, carpenter ant galleries) has not been widely explored. Habitat sculptures can attempt to replicate these structures while exploring their unique forms artistically. Creating artificial structures that replicate cavities in woody stems and reeds also provides an opportunity to create visually interesting sculptural forms. Dead wood is readily colonized by wood boring insects, so inclusion of natural dead trees and logs into the form of habitat sculptures may be the best way to reproduce these alternative cavities. However, the forms of the cavities themselves are artistically interesting, as demonstrated by the ant mound casts of Walter R. Tschinkel and others (Figure 18). Although these natural habitat structures have not been studied as candidates for artificial replication, there may be a chance that cavity-dwelling communities would reside in structures that mimic natural cavities in other materials.

Figure 18. Metal casts by myrmecologist Walter R. Tschinkel showing the internal structure of ant nests. Sources: (left) photograph from Charles F. Badland, 2006; (right) Tschinkel (2021).

A method I am proposing to create these alternative artificial cavity structures draws on an age-old metal casting technique called lost-wax casting. The first step is to identify a salvaged piece of dead wood. This technique is destructive so it should not be used on dead wood that is full of living organisms. Next identify bore holes from large wood boring insects such as longhorn beetles (*Cerambycidae*) or carpenter ants (*Camponotus*). Cast a molten metal such as bronze into the bore hole. Once the metal has cooled, burn away the log, leaving behind a bronze cast of the insect tunnel or gallery. Next make a flexible rubber mold of the metal cast. Remove the metal and cast a water soluble, biodegradable, or nutrient-rich material into the rubber mold. Cast something around it like woodcrete, and either dissolve away the gallery cast or leave it to be consumed. I am calling this technique *lost-log casting*.

Water-filled Tree Cavities (Dendrotelmata)

When large tree hollows fill with water, they become known as *dendrotelmata* or water-filled tree holes (Figure 19). Many dendrotelmata are temporary, but some can persist for years or even decades (Kitching, 2000). They can range in size from 3 mL to 30 L. In some rare cases, entire trees or logs can be water-filled. According to Kitching (2000), water in dendrotelmata can be permanent in cavities exceeding 10-20 cm in internal diameter. Patterns of evaporation and rainfall also dictate the ephemerality of water in dendrotelmata (Kitching, 2000). Basins and depressions that form on tree branches and roots and fill with water are called *pans*, which are also classified as dendrotelmata in the scientific literature. They have similar ecological functions but have quite different forms in the context of sculpture (Figure 19; Kitching, 1971).

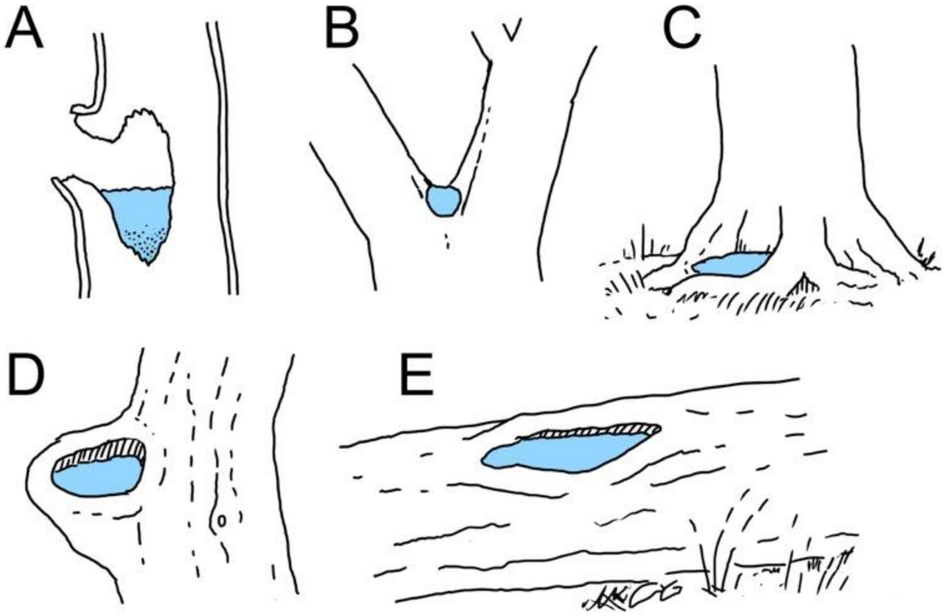

Figure 19. Types of dendrotelmata. A) rot hole dendrotelmata shown in cross-section, B) branch pan, C) root pan, D) bowl-shaped dendrotelmata, E) log hole. Source: RJH Artworks, 2022

These arboreal pockets of water are ecologically important in several ways. First, they provide a reliable water source for many animals, even during dry spells when other water sources may be depleted (Delgado-Martínez *et al*., 2022). Delgado-Martínez *et al.* (2022) found at least 21 vertebrate species utilizing dendrotelmata in a forest in Mexico, consisting of 12 bird families and eight mammal families, as well as numerous bat species that were not identified. Kirsch *et al.* (2021) found 28 vertebrate species using dendrotelmata in a temperate forest in Germany, including one amphibian, 17 birds, and 11 mammals. These authors also found dendrotelmata with water volumes over 200 mL to be the most useful for vertebrates. This measurement can be used in habitat sculptures that are targeting vertebrate species. Non-aquatic invertebrates such as wasps, bees, beetles also use dendrotelmata as sources of hydration (Kirsch *et al*., 2021). Aside from hydration, animals use these structures for bathing, thermoregulation, and foraging. Amphibians such as salamanders (Urodela) and tree frogs (Hylidae) are known to breed in dendrotelmata in tropical regions, and they may use dendrotelmata in logs (known as *log holes*) in temperate regions (Kitching, 2000; Kirsch *et al*., 2021). Gossner *et al.* (2020) found that dendrotelmata are important food sources for birds and other animals because of the rich arthropod communities that inhabit them.

Dendrotelmata host unique and ecologically important communities of aquatic and semi-aquatic invertebrates (Kitching, 2000). Like mould-filled hollows, some of the organisms in dendrotelmata are specialists that can’t be found in any other environment, while others are non-specialist species that also inhabit vernal pools, wetlands, ponds, and streams. Dendrotelmata are considered *container habitats* because entire food chains and ecosystem dynamics exist inside them in a relatively self-contained manner (Kitching, 2000). Taxonomic groups from across all domains of life are represented in dendrotelmata. These most prevalent include rotifers, annelid worms, tardigrades, crustaceans, insects, arachnids, and mollusks. These organisms depend on a steady stream of nutrient inputs via rain and leaf litter entering the holes (Gossner *et al*., 2016). Leaf litter enters tree holes and is broken down by fungi and other organisms, forming the primary food resource (Kitching, 2000). Gossner *et al*. (2016) found that detritus amount and water chemistry were the two most important factors affecting species composition in dendrotelmata. Habitat sculptures that incorporate these forms should have entrance holes that are relatively large, and oriented slightly upward to maximize species richness and abundance. As with other habitat structures covered in this research, including a diversity of forms may be the best approach to provide habitat for different specialist species.

Important water chemistry factors that affect species composition in dendrotelmata include pH and dissolved oxygen (Kitching, 2000; Gossner *et al*., 2016). The pH of dendrotelmata waters range from slightly alkaline to highly acidic (Kitching 2000). Hoverfly (Syrphidae) larva prefer neutral to slightly alkaline water, while different mosquito species cover a wide range of acidity preferences but tend to dominate in highly acidic waters (Kitching, 2000). Algae cultures sometimes cause the water to become more alkaline, which could be useful for modifying pH in habitat sculptures mimicking dendrotelmata (Kitching, 2000). Temperature is especially important in container habitats because the small water volume provides less thermal buffering than larger water bodies. Temperature also affects dissolved oxygen, which is a necessary resource for many aquatic organisms (Kitching, 2000). Thicker walls and more mass in habitat sculptures will create more thermally stable dendrotelmata, which would protect organisms from harmful fluctuations (Bradshaw & Holzapfel, 1984).

Other structural factors affecting the organisms in water-filled tree holes include height above ground, sun exposure, and cavity volume (Gossner *et al*., 2016). Biotic factors include surrounding plant diversity and canopy cover. Smaller vegetation such as herbaceous plants and grasses can provide important food and shelter resources (Kitching, 2000). For instance, hoverfly larvae commonly develop inside dendrotelmata, but adults leave the cavities to feed on pollen (Gossner *et al*., 2016). Habitat sculpture installations will need to include flowering plants or be located near flowering plants for these insects to complete their lifecycles.

The small scale and self-contained nature of dendrotelmata make them ideal structures to include in habitat sculpture. They support a wide range of wild organisms from large vertebrates to microbes, and they are being destroyed by human land use and cultural practices just like other habitat structures associated with large old trees (Lindenmayer *et al*., 2012; Le Roux *et al*., 2014). There is also ample scientific research on the subject to draw from for sculpture design and creation. However, the prevalence of mosquitos in dendrotelmata greatly complicates the use of these structures in human-occupied areas.

In nature, numerous species of mosquito use dendrotelmata for breeding including species that transmit mosquito-borne diseases, known as *vector mosquitos* (Kitching, 2000). In the northeastern USA, vector mosquito species that breed in dendrotelmata include eastern tree hole mosquitos (*Ochlerotatus triseriatus*), Asian bush mosquitos (*Ochlerotatus japonicus*), common house mosquitos (*Culex pipiens*), white-dotted mosquitos (*Culex restuans*), forest mosquitos (*Aedes albopictus*), and yellow fever mosquitos (*Aedes aegypti*) (CDC, 2017; Massachusetts, 2018). The abundance and number of vector mosquito species is higher in the tropics and subtropics than in temperate regions (Kitching, 2000; Bartlow *et al*., 2019). Many of these tropical species are increasing their range northwards as anthropogenic climate change takes effect (Bartlow *et al*., 2019). Mosquito-borne diseases such as malaria have been a major cause of human suffering and death throughout history, and these diseases are increasingly spreading in urban areas as invasive vector mosquitos spread around the globe (LaDeau *et al*., 2013; Bartlow *et al*., 2019). Although habitat sculptures would likely represent an insignificant fraction of artificial mosquito-breeding territory in human-occupied areas, every effort should be made to avoid actively contributing to populations of vector mosquitos, especially in low-income neighborhoods. Research has consistently found that low-income neighborhoods are disproportionately affected by vector mosquitos, likely due to high rates of discarded containers that serve as habitat analogs (Dowling *et al*., 2013; LaDeau *et al*., 2013; Little *et al*., 2017).

The association of water with vector mosquitos creates a fundamental problem for incorporating nature into human-occupied areas (Kiel *et al*., 2019). Many resources exist for mosquito control strategies, but most focus on entirely eliminating container habitats, which is not an approach compatible with providing the necessary resources for wild organisms to survive in human-occupied areas (Keil *et al*., 2019). Alternative mitigation efforts include water agitation, targeted insecticide application, and intensive monitoring (Little *et al*., 2017). Srivastava & Lawton (1998) and Yanoviak & Fincke (2005) provide detailed methodologies for monitoring dendrotelmata for mosquitos specifically.

When combined with elimination of existing mosquito breeding pools, artificial dendrotelmata incorporated into habitat sculptures may be able to reduce vector mosquito populations overall by providing more naturalistic habitat analogs that boost the abundance of their natural predators. Mosquito breeding pools are often superabundant in human-occupied areas (Dowling *et al*., 2013). These include discarded tires, buckets, pieces of trash, and countless other structures that fill with water (Yee, 2008; LaDeau *et al*., 2013). Partly because these analogs depart so drastically from the conditions in natural dendrotelmata, they are often dominated exclusively by vector mosquitos that live among humans (Yee, 2008). Replacing these mosquito-dominated containers with more naturalistic habitats may have positive effects by providing habitat to a full array of aquatic invertebrates, including predators of mosquitos such as dragonflies (Odonata) and predatory non-biting mosquitos. Providing naturalistic water sources in habitat sculptures may also have a positive effect on vertebrate predators of mosquitos like birds and bats. These creatures may be able to make more effective use of naturalistic water containers than the containers with unnatural properties that mosquitos can dominate.

Habitat sculptures may be able to create more naturalistic dendrotelmata analogs in multiple ways. The first technique is incorporating salvaged dendrotelmata, as has been discussed for tree hollows and mould-filled cavities. Creating artificial dendrotelmata carved out of wood, or cast from rubber molds of natural dendrotelmata, may impart needed characteristics. Because water chemistry is such an important factor affecting species composition, material choice may be more impactful than in other structures (Gossner *et al*., 2016). When using artificial materials such as concrete, covering the surfaces where the water meets the material with bark may impart a more naturalistic water chemistry (Van Stan *et al*., 2021). Cement and other material mixtures can be made with specific pH and nutrient levels to target or exclude certain species. These techniques are as yet untested in the context of sculpture, but a sculptural approach may allow for flexibility and rapid iteration. Collaborating with experienced researchers on these structures may also lead to new techniques and innovations.

Pans, Puddles, Sartenejas, and Basins

While the dendrotelmata described above are shaped like cavities, other natural structures that gather water are shaped like basins, crevices, and other concave forms that are open on top (Figure 19). Root pans and branch pans have been studied along with other dendrotelmata in the scientific literature, so there is ample information that can be drawn on for replication of these resources in habitat sculpture (Kitching, 1971; Kitching, 2000; Gossner *et al*., 2016; Kirsch *et al*., 2021). Information about structural and biotic factors that affect species composition is especially useful. Small depressions in the ground that form puddles, marine tidepools, and crevices in rock that gather water known as *rock holes* or *sartenejas* (pronounced sart-ehn-AY-has) all have unique ecological functions that can be studied and replicated in habitat sculpture (Calhoun & DeMaynadier 2007; Little *et al*., 2017; Delgado-Martínez *et al*., 2018).

These structures are used by a wide variety of organisms for drinking, bathing, thermoregulation, and foraging (Epaphras *et al*., 2008; Delgado-Martínez *et al*., 2018). Puddles on the ground can often be nutrient-rich and may be an important source of minerals and nutrients for vertebrates such as bats (Bravo *et al*., 2010). Amphibians such as frogs use puddles for reproduction and development (Cunningham, 1963). Many invertebrates such as butterflies use puddles for nutrition and hydration (Sculley & Boggs, 1996). Delgado-Martínez *et al*. (2018) revealed that sartenejas in Mexican forests are far more essential for vertebrates as a water source than had been previously known. As with dendrotelmata, each of these structures host aquatic insect fauna, some specialists, and some generalists. These include many species of mosquito, some of them vector species (Dăncescu *et al*., 1980; McLachlan & Ladle, 2001). Similar precautions as described above should be taken with these structures when they are included in habitat sculpture installations. This includes monitoring and maintenance.

Most of the structures mentioned above are shallow and basin-like, except sartenejas which tend to have a deep wedge-shaped form (Delgado-Martínez *et al*., 2018). The shallow edges of these structures seem to be an important physical characteristic that allow animals to access the water without slipping in (Mayntz, 2020). As with many of the habitat structures discussed previously, height, sun exposure, other thermal properties, canopy cover, and surrounding vegetation are likely to have significant effects on ecological functioning. In particular, height above the ground will dictate which species can physically access the water. These structures can be replicated in range of materials such as dirt, clay, stone, cement, and wood. Salvaged natural structures such as rocks may be used, but as with other salvaged habitat structures, care should be taken to not harm to wild organisms by removing salvaged structures when they are already present and functioning in existing ecosystems. This technique does not apply to soil structures like puddles, but molds could conceivably be made when these structures are dry to capture naturalistic dimensions and forms.

Existing artificial analogs of these small water sources such as birdbaths are commonly seen to supply water to a wide range of vertebrates, but there is little scientific research on the subject (Mason & Macdonald, 2006; Miller *et al*., 2015). Conservation organizations recommend regularly cleaning birdbaths to prevent the spread of avian diseases (Cleary *et al*., 2016; Purple, 2018). The role of birdbaths in spreading avian disease is still largely unknown, but future research will hopefully shed light on this question. Regular cleaning precludes the possibility of using these structures to provide habitat to aquatic invertebrates, which may be desirable in certain circumstances. However, this approach does not align with the multi-species approach of habitat sculpture installations. It may be desirable to compromise by cleaning basins that are used most often by birds while not cleaning basins that birds are unable to access. Using running water pumped into basins is another way to prevent microbial and in invertebrate communities from forming, but it is also recommended that running water systems be cleaned regularly for effective pathogen prevention (Mayntz, 2020).

Larger water bodies such as vernal pools, ponds, streams, etc. are ecologically important but too large to be incorporated into discrete sculptural objects. They can, however, be included as additional resources in habitat sculpture installations (see section 3.3.1). They can also be considered under a more inclusive definition of sculpture that includes earthworks and land art. The boundaries between 'sculpture' and 'site' are inherently blurry in ecological artworks like habitat sculptures, and using soil as a medium blurs the boundaries further (Figure 38). These larger water sources will be discussed further in section 3.3.1.

Other Concave Structures

The concave structures that have been covered here are just a fraction of the possible natural forms that could be studied and replicated in habitat sculpture. Artists should draw inspiration from their surroundings and look out for signs of animals and other organisms using these protected pockets. Other concave structures in nature that could be relevant to habitat sculpture include water-holding plants known as *phytotelmata*, insect-created structures; and large tunnels and burrows made in the ground.

Phytotelmata include plants from many different taxa, all with the capacity to hold water. Kitching (2000) defines five broad categories of phytotelmata: bromeliad tanks, pitcher plants, dendrotelmata, bamboo internodes, and axil waters (Figure 20). Dendrotelmata have been discussed in detail, but other subcategories of phytotelmata each have unique species assemblages and ecological roles associated with them (Kitching, 2000). Each could possibly be incorporated into habitat sculpture. Plants belonging to the other subcategories of phytotelmata are largely restricted to tropical and subtropical regions (Kitching, 2000). A notable exception in the northeastern USA is the purple pitcher plant *(Sarracenia purpurea*), which is capable of hosting at least 165 species of arthropod, bacteria, protist, algae, etc. because of its low acidity compared to other pitcher plants (Adlassnig *et al*., 2011). Because these structures are made of living vegetation, many of their characteristics may be impossible to reproduce in static sculptures. Only exploration and experimentation will tell what is possible and what is not.

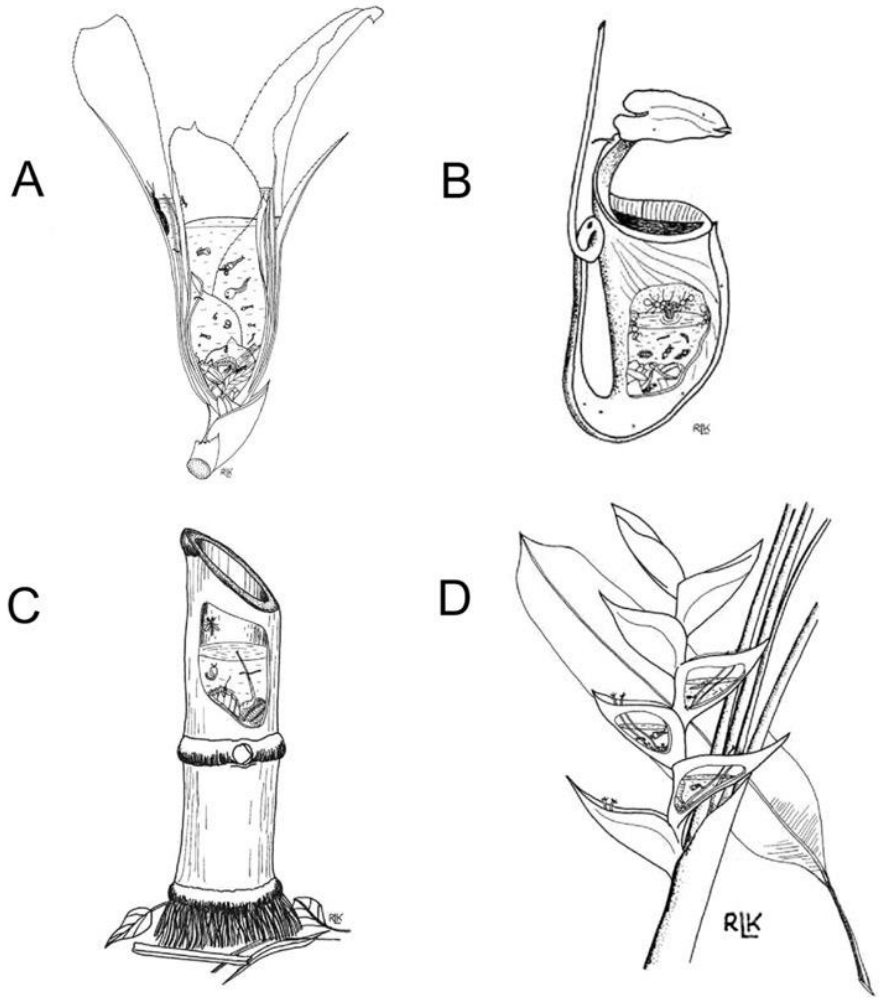

Figure 20. Four types of phytotelmata. A) bromeliad tank, B) pitcher plant, C) bamboo internode, D) axil waters. Source: modified from Kitching (2000).

Cavities excavated in wood and soil have been discussed, but there are many other ecologically important habitat structures created by insects, such as leaf rolls[4], galls, wasp and bee nests, ant mounds, and termite mounds (Cornelissen *et al*., 2016). Cornelissen *et al*. (2016) showed that aside from the insects that create them, many arthropods use these structures once they are abandoned. The presence of insect-built shelters was shown to increase arthropod species richness and abundance in location where these structures were plentiful (Cornelissen *et al*., 2016). Although little research has been done on artificial replication, these structures are aesthetically interesting and may have potential for inclusion in habitat sculptures (Figure 21).

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[4] Leaf rolls are simple structures constructed by larval insects by covering, tying, folding, cut-and-folding, or rolling plant leaves with silk (Cornelissen *et al*., 2016).

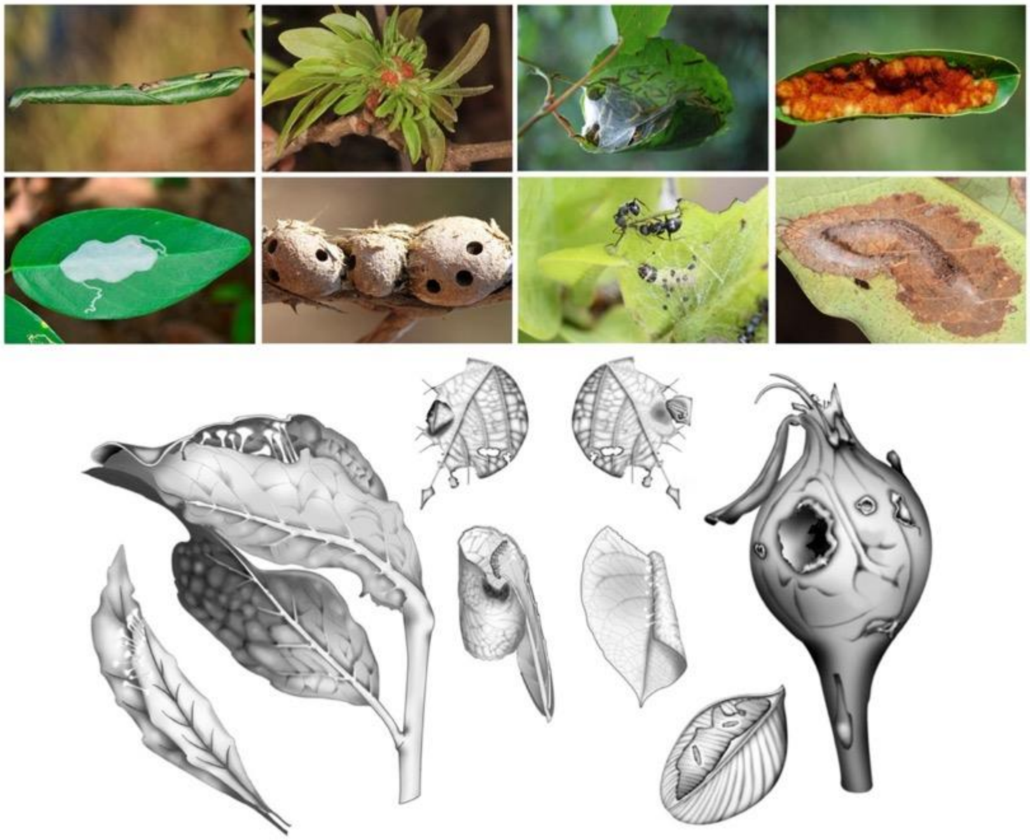

Figure 21. Photographs and illustrations of shelter-building insect structures. Source: modified from Cornelissen et al. (2016).

Tunnels and burrows made in the ground by animals like chipmunks, woodchucks, prairie dogs, gopher tortoises, rabbits, and others are keystone habitats used by many other creatures (Grillet *et al*., 2010; Kinlaw & Grasmueck, 2012). Burrows created by the gopher tortoise (*Gopherus polyphemus*) host over 300 species of vertebrates and invertebrates (Kinlaw & Grasmueck, 2012). Anthropogenic pressures such as land use and habitat destruction have caused population declines in many of these burrowing species, thereby causing declines in the group of species who depend on their burrows such as the endangered black-footed ferret (*Mustela nigripes*) (Grillet *et al*., 2010). Artificial burrows have been created for many of these animals, some even targeting multi-species assemblages (Alexander *et al*., 2005; Grillet *et al*., 2010; Ebrahimi *et al*., 2012). The underground nature of these structures, and the necessity for their entrances to be hidden from predators makes them challenging to incorporate into sculpture installations. There may, however, be opportunities with structures that are built up into artificial mounds rather than being dug into the earth (Figure 22; Fernández-Olalla *et al*., 2010). Similar structures will be discussed in section 3.1.2. The fundamental conflict between sculptures that are meant to draw attention and habitat structures that are meant to provide refuge and protection from disturbance is especially present in ground burrows. Not all habitat structures are suitable for inclusion in habitat sculpture installations, but which of them are suitable and which are not remains to be seen through experimentation.

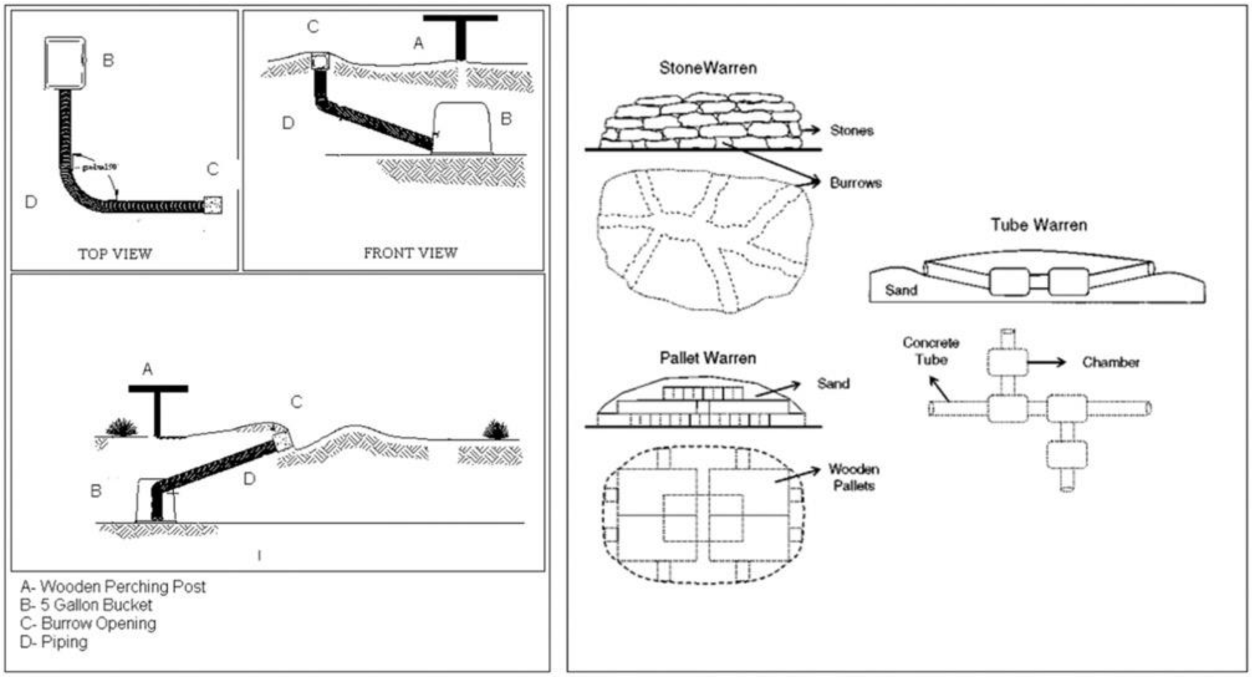

Figure 22. Schematics showing artificial burrows for burrowing owls in Washington, USA (left) and wild rabbits in Spain (right). Sources: (Left) Alexander et al., 2005; (right) Fernández-Olalla et al., 2010.

3.1.2 Interstitial Spaces

Interstitial spaces are gaps and crevices that form between closely spaced objects. This section will examine ecologically relevant interstitial spaces in the natural world, how they are used by certain organisms, artificial analogs that successfully imitate them, and how these spaces can be used or replicated in sculpture. Interstitial spaces are used by organisms for shelter in much the same way as concave forms are used (Jaeger, 1990; Cove *et al*., 2017). Some of them could be considered concave forms from a certain point of view, but there are important physical and ecological differences. Sculpting these forms also requires entirely different methods than the ones used for sculpting shapes like tree hollows or insect galleries. The concavities covered in the last section could all be carved into solid objects, but interstitial spaces occur when different objects are put together. This means that it is an additive sculptural process rather than a subtractive one. While concave habitat structures require sculptors to concentrate on the negative space being created inside positive forms, interstitial spaces allow sculptors to focus on positive forms which then create negative spaces by virtue of their placement relative to other forms.

Cover Objects

Perhaps the simplest interstitial space is the one between an object and the ground. Most sculptures have a point where they meet the ground, but in habitat sculpture this interface takes on a special significance. Rather than using pedestals or mounts to mediate this interface, habitat sculptures can shape it to create an ecologically active interstitial space. By determining which variables and conditions impact the ecology of these interstitial spaces, sculptors will be able to shape them in the most beneficial way.

Anyone who has ever kept their eyes peeled while flipping over large rocks or turning over logs in the woods has seen diverse assemblages of secretive creatures scramble for cover or dig into the ground. The rocks, pieces of wood (known as *woody debris*), vegetation, and other objects that hide these creatures in nature are known as *cover objects* (Willson & Gibbons, 2010). Scientists have used artificial cover objects known as *coverboards* for decades to monitor and collect certain organisms such as salamanders, but recent work has investigated using artificial cover objects in a more sustained and systematic way for conservation purposes (Cowan *et al*., 2021; Watchorn *et al.*, 2022). Along with studying natural habitat preferences and conditions, insights from this research will be informative for habitat sculpture design.

Cover objects are used by organisms to avoid predation, to forage for invertebrates and other small prey, and by creatures seeking certain microclimates (Jaeger, 1990; Hodges & Seabrook, 2016a; Haggerty *et al*., 2019). Cover objects on soil trap moisture, creating wet microclimates that are sought out by creatures who are vulnerable to desiccation such as amphibians, invertebrates, and fungi (Haggerty *et al.*, 2019). During rainy weather some of these creatures venture out to feed, breed, and migrate, but during dry spells these cover objects become crucial refuges (Jaeger, 1980). Habitat sculptures using stone or wood will replicate this moisture-trapping ability, but other materials should be explored as well. When stones and other objects are sitting on rocky surfaces rather than moist soil, they can absorb heat and create especially warm and dry microclimates. These are favored by reptiles and other heat-loving and desiccation resistant creatures (Lettink & Cree, 2007).

The invertebrate community under cover objects is a mixture of terrestrial species, ground-dwelling species, and species that specialize on this liminal space (Lunt, 2004). A waxy water-retaining cuticle is a defining feature of adult insects, so moist cover object communities tend to be dominated by non-insect invertebrates and insects in juvenile stages who are still vulnerable to desiccation (Ulyshen, 2018a). This congregation of invertebrates attracts small predators such as snakes and salamanders who can fit in these spaces and maneuver in the soil (Jaeger, 1990). Haggerty *et al*. (2019) showed that a lack canopy and vegetation cover can dry out these moist microclimates, desiccating the creatures who rely on them. Habitat sculptures that are aiming to create moist cover object refuges should in general maximize shade from these sources, but creating a variety of shade conditions may be beneficial for overall community diversity (Loke *et al*., 2015).

Artificial Cover Objects

Artificial coverboards for monitoring amphibians typically consist of plywood sheets, ranging from small pieces (20 x 30 cm) to long thin strips (200 x 25 cm) to large plywood sheets (240 x 120 cm) (Moore, 2005). These moisture-trapping structures successfully attract target organisms by imitating woody debris, but capture rates under these structures tend to be lower than under natural cover objects (Moore, 2005; Willson & Gibbons, 2010). Including more naturalistic features like thicker wood and wood from native tree species has been shown to increase the habitat value of these structures (Moore, 2005).

Coverboards for reptiles are typically made of sheet metal and other materials that absorb heat like garage felt, thereby replicating large flat sun-exposed rocks rather than moist woody debris (Willson & Gibbons, 2010). Lettink & Cree (2007) tested concrete tiles, Onduline tiles (a petroleum-based roofing material), and corrugated iron tiles. They found that common geckos (*Hoplodactylus maculatus*) preferred Onduline tiles for their thermal properties, but other lizards showed no preference (Figure 23). Metal that is exposed to the sun may dry out these refuges so they are not suitable for non-reptile species, but creating a variety of microclimates with different thermal conditions and moisture levels may also be beneficial for accommodating a wider variety of species (Hodges & Seabrook, 2016a).

Figure 23. Artificial cover objects. Source: Lettink & Cree, 2007.

Reptiles such as snakes use cover objects mainly as protection from predators (Hodges & Seabrook, 2016a). Many reptiles need direct sunlight for thermoregulation, so they must periodically leave the safety of cover objects to seek basking surfaces (Gaywood & Spellerberg, 1995). Preferred basking sites are always close to cover objects and vegetative cover so the reptiles can make a quick escape (Hodges & Seabrook, 2016b). Hodges and Seabrook (2016a-c) undertook an 8-year study testing artificial coverboards for the common European viper (*Vipera* *berus*). They tested whether providing coverboards made of corrugated tin roofing, which heats up in the sun, allows snakes to thermoregulate without exposing themselves to predation risk in the open. Overheating from these structures is a negligible concern with reptiles like snakes who are highly mobile, as long as there are other thermal environments they can travel to in safety (Hodges & Seabrook, 2016b). Hodges and Seabrook (2016c) further amplified the heating effect of the tin roofing by placing an insulating mat underneath half of the tin coverboards. This created two distinct thermal environments under the coverboards, creating habitats that appeared to be heavily utilized by the snakes. Metals such as steel are common sculpture materials, but they do not possess many characteristics that make them suitable for habitat analogs. Using metal sheeting to create unnaturally warm microclimates for reptiles is an interesting example of how the novel properties of this artificial material can be used to benefit organisms.

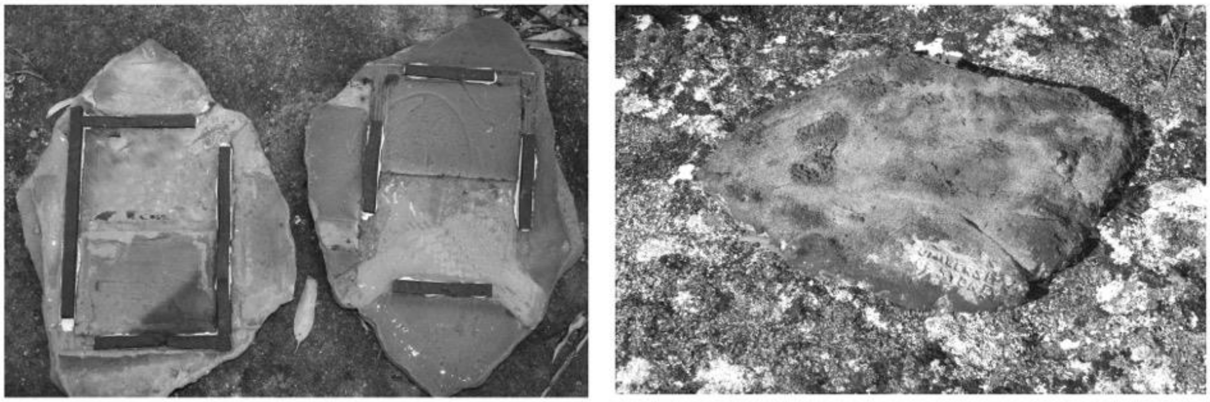

Figure 24. Artificial habitat rocks made of cast cement. Source: Modified from Croak et al.*, 2010.*

Another novel material application for cover objects is the use of cast concrete to replicate specific rocks. Croak *et al*. (2010) made rubber molds of rocks used by the broad-headed snake (*Hoplocephalus bungaroides*). These thin sandstone rocks are critical habitat structures for these snakes and many others in the sandstone outcrops of southeastern Australia. Sadly, these rocks are being taken at an unsustainable rate for use in landscaping and gardening. The rocks the authors chose for replication were thought to have ideal structural and thermal properties for the broad-headed snake. The authors wanted to see if cast concrete duplicates would retain these thermal and ecological properties. The results showed that the thermal regimes of the artificial rocks perfectly matched those of the natural rocks, and nearly all the rocks were being used by a variety of vertebrate and invertebrate species. One detail of note is the foam tape (Figure 24, left) the authors used the create gaps of 4-6 mm between the rocks and the ground. This study shows that making cement casts of natural cover objects like rocks can be very successful and opens many possibilities for using similar techniques in habitat sculpture.

Habitat sculptures should seek to replicate natural cover objects rather than artificial coverboards, but coverboards are valuable for showing which factors are important for interstitial fauna. Using naturally decaying woody debris in habitat sculptures rather than manufactured lumber for the point of contact with the ground may have many benefits (see section 3.3.4). Michael *et al*. (2004) and other authors have experimented with placing logs in degraded habitats and found that they are readily used by a wide variety of interstitial fauna, with difference in species assemblage based on the age and species of the logs (Márquez-Ferrando *et al*., 2009; Goldin & Hutchinson, 2014).

As with other habitat structures, woody debris and other natural cover objects should not be disturbed for the sake of habitat sculptures, but salvaged cover objects that are destined for disposal may be plentiful. Making molds of natural cover objects for replication yields distinct advantages, as does the 3D scanning and printing of these objects (Croak *et al*., 2010; Parker *et al.*, 2022). These non-destructive replication methods allow for a degree of complexity and detail that have been shown to be ecologically beneficial, but they may also be artistically compelling. Cast pieces that replicate cover objects could be combined with sculpted elements or be directly modified by sculptors to create new forms that meld habitat functionality with artistic effects.

Refugia and Hibernacula

In nature many organisms can be found in the interstitial spaces created by piles of rock, decaying root systems, and piles of branches and woody debris known as *brush piles*. Although there are examples of piles that are purely rock, or purely wood, in nature these piles can contain a mix of rock, wood, soil and vegetation. Organisms use these structures for shelter, nesting, breeding, and hibernation (Cove *et al*., 2017). These structures are collectively known as *refugia* when they are used by organisms for shelter, but refugia can also be used to refer to any cover object an organism uses for shelter (Hodges & Seabrook, 2016a). I will be using this term to refer specifically to the more structurally complex piles of materials and debris rather than to rocks and logs. When refugia are specifically used by organisms for hibernation, they are called *hibernacula* (Zappalorti *et al*., 2014). In human-occupied areas, many organisms have been found making use of discarded items and trash piles as artificial analogs of refugia and hibernacula (Zappalorti & Reinert, 1994; Cove *et al*., 2017). Piles of rock used in construction for erosion control known as *riprap* are also used as successful artificial analogs of rock piles (Schulz *et al*., 2012; Johnson, 2019).

Organisms that use refugia tend to be ground-dwelling, and there is overlap between organisms that use refugia and those that use subterranean burrows and tunnels (Grillet *et al*., 2010). Refugia faunae tend not to be strong excavators and will switch between abandoned ground burrows and refugia opportunistically (Grillet *et al*., 2010). Refugia users will also use hollowed-out trees and logs opportunistically. Except for generalist species such as raccoons, ground-dwelling refugia users do not have much overlap with tree-dwelling cavity users (Zappalorti *et al*., 2014). Refugia-using species in the northeastern USA include reptiles (most often snakes), amphibians such as salamanders and frogs, small rodents, and medium-sized mammals such as Virginia opossums (*Didelphis virginiana*) and North American porcupines (*Erethizon dorsatum*), (Latham & Knowles, 2008; Zappalorti *et al*., 2014; Cove *et al*., 2017).

Different taxa have different requirements that affect their use of refugia. For amphibians, the most important factors influencing choice of refugia include the distance to the nearest water source, thermal stability, and moisture levels (Dervo *et al*., 2018). Thermal stability is a crucial factor for any animal using these structures as hibernacula, but especially for ectothermic creatures like reptiles (Zappalorti & Reinert, 1994). Amount of sunlight on the structure and proximity to basking surfaces are also important factors for reptiles (Zappalorti *et al*., 2014). Proximity to foraging areas is also important for refuge-dwellers (Grillet *et al*., 2010). Just as with cover objects, invertebrate communities inside refugia are species-rich and ecologically important as decomposers, and as a food source for vertebrate species (Ulyshen, 2018b; Tóth *et al*., 2019). Refugia covered with soil may create important microhabitats for plant species as well (Tóth *et al*., 2019).

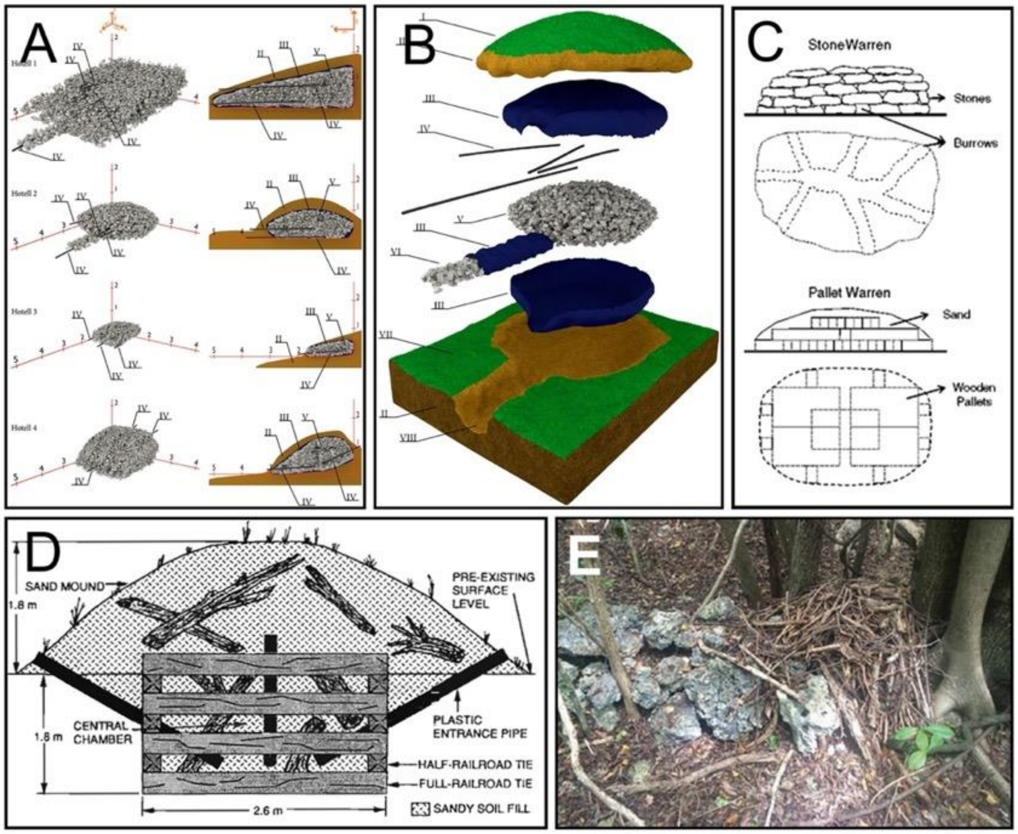

Figure 25. Artificial refugia and hibernacula designs. A, B) newt hotel designs, C) artificial rabbit warren designs, D) hibernacula design for snakes, E) refugia for rodents. Sources: A, B) Dervo et al., 2018; C) Fernández-Olalla et al., 2010; D) Zappalorti & Reinert, 1994; E); Cove et al., 2017.

Artificial refugia and hibernacula have been made for species including snakes (Zappalorti *et al*., 2014), lizards (Grillet *et al*., 2010), newts and salamanders (Dervo *et al*., 2018), medium-sized mammals (Fernández-Olalla *et al*., 2010; Schulz *et al*., 2012), and small rodents (Figure 25; Cove *et al*., 2017). These structures create interstitial space by piling natural materials like rocks and wood debris. They control moisture levels with water barriers like plastic sheets, and with drainage infrastructure (Dervo *et al*., 2018). Thermal stability is achieved by digging into the ground to start the structure and piling soil and vegetation on top of the looser material to create an insulated mound shape. Some designs use geotextile fabric to keep the soil on top from filling in the interstitial space in the larger aggregate below (Dervo *et al*., 2018). Most designs use PVC tubes that lead directly into the large aggregate chamber to create entrances for target organisms (Zappalorti *et al*., 2014; Dervo *et al*., 2018).

As with other utilitarian artificial habitat structures, habitat sculptures should take lessons and ideas from these artificial refugia and hibernacula but not be limited by their forms and techniques. The underground portion of the structure could come directly from these designs, but the above-ground portion could be radically different, possibly incorporating other habitat structures to target multi-species assemblages.

The fine-grained complexity of interstitial spaces in refugia present an opportunity for sculptors to embrace a visual aesthetic of complexity that melds artistic and ecological aims. Complexity is a central theme in habitat sculpture, and the small-scale dense complexity of refugia lends itself to a kind of emergent form that takes shape out of many small pieces. The dominant aesthetic attitudes of modern American culture do not value dense and messy habitat structures like brush piles (Rosenzweig, 2003). Habitat sculptures can circumvent expectations about these structures and cause viewers to pay closer attention in a way that may change attitudes. This can be accomplished by deviating enough from the natural appearance of these structures that intentionality is shown. Creating an underlying framework that suggests an order and logic to the chaos of the debris pile is one way to differentiate a habitat sculpture from an ordinary debris pile in the mind of the viewer. Incorporating patterns and complex geometries shows an underlying order while maintaining structural complexity for ecological purposes. Keeping refuge piles chaotic but forming them into larger sculptural shapes also suggests order and intentionality. Another strategy to show intentionality is to push the complexity of these structures into an extreme state of chaos that would be unlikely to occur in nature. A brush pile with thousands of branches, rocks, and artificial items reaching high into the air would be an example of this. Showing intentionality could also be as simple as placing a skillfully crafted sculptural element into the center of a chaotic refugia (see section 3.4).

Crevices

Crevices can occur between two objects that are pushed together, or they can be wedge-shaped spaces gouged into solid objects. Like the other negative spaces discussed so far, these structures primarily provide shelter, albeit to a physically smaller cohort of organisms. For invertebrates and other small creatures, crevices function like the interstitial spaces beneath cover objects, only they can be vertical in orientation and are generally less moist because they are not trapping moisture coming up from the ground. While this creates a less favorable microclimate for moisture-loving creatures like amphibians and non-insect arthropods, these spaces create more separated niches for desiccation resistant invertebrates like adult insects and the creatures who prey on them. When oriented horizontally, these spaces can fill with water, dirt, and other organic debris, creating small pockets that allow plants and fungi to make use of vertical space (Lundholm & Richardson, 2010). Some of the most ecologically important crevices that are relevant to habitat sculpture are crevices in rock, crevices in built structures, and crevices beneath exfoliating bark.

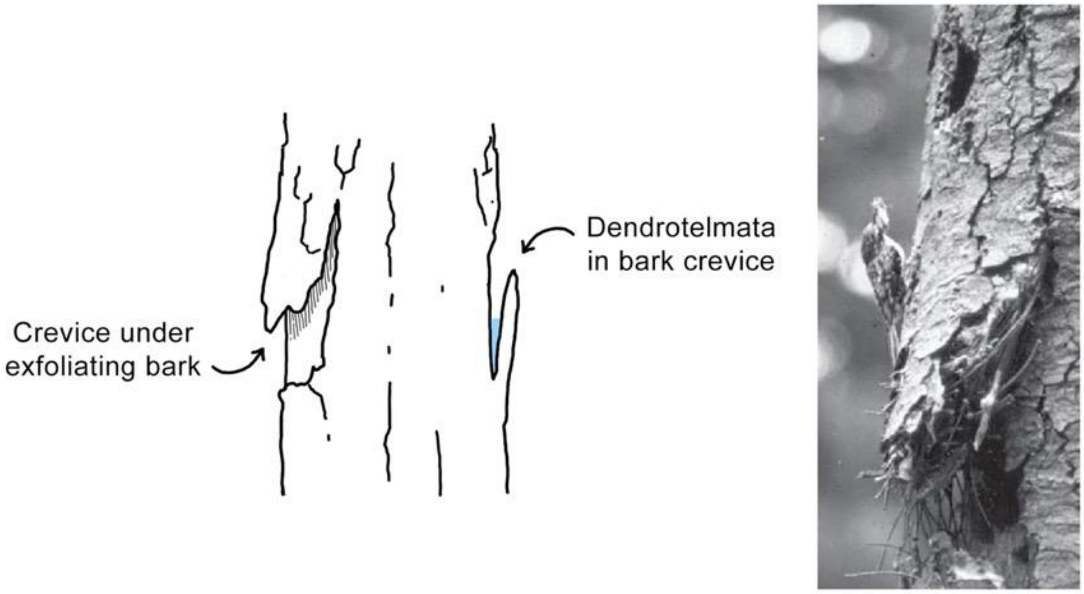

Figure 26. (Left) exfoliating bark provides roosting sites for bats, and exfoliating bark oriented upward can create unique dendrotelmata water sources; (right) photo of a brown creeper (Certhia americana) using a crevice nest. Source: (left) RJH Artworks, 2022; (right) Rose et al. (2001), photograph by Karen L. Waddell

Exfoliating Bark

Tree bark that has started to peel off (called *exfoliating bark* or *sloughing bark*) creates a crevice space between the bark and the tree (Figure 26). This space is sheltered from predators and adverse weather, and so is used as a roosting site by many bats (Lacki & Schwierjohann, 2001; Gumbert *et al*., 2013). There are also some crevice-nesting birds such as the brown creeper (*Certhia americana*) (Figure 26; Stokland *et al*., 2012). Like other habitat structures associated with dead and dying trees, pieces of exfoliating bark are scarce and getting scarcer in human-occupied areas, threatening bat species who depend on them (Lindenmayer *et al*., 2012).

For bats roosting under exfoliating bark, temperature is thought to be the most important factor in site selection (Adams *et al*., 2015). Temperatures under 15° C can cause bats to go into torpor, and temperatures over 40° C can cause overheating and death in extreme cases (Rogers, 2020). Bats prefer warmer roosts, and so tend to roost in snags exposed to full sunlight (Rogers, 2020). Different species of bat likely have different preferences for the height of roosts, but heights between 6 and 9 m seem to be preferred by *Myotis* bats in North America (Hoeh *et al*., 2018; Rogers, 2020). In experiments, bats seem to prefer larger roosts with large entrance areas and interior volumes (Hoeh *et al*., 2018). Bats prefer dark roosting sites away from artificial light (Zeale *et* al., 2016). Proximity to food and water is another important factor in where bats will decide to roost (Tuttle *et al*., 2005; De La Cruz *et al*., 2018).

Analogs of exfoliating bark include loose siding on houses, roof tiles, and a variety of other structures with suitable crevices (Gumbert *et al*., 2013). These artificial analogs boost bat populations, but negative perceptions of bats and concerns over disease spread make these roosts undesirable in most cases (Zeale *et* al., 2016; Arias *et al*, 2020). At the same time, artificial roosts have become very popular in recent years (Figure 27; Martin, 2021).

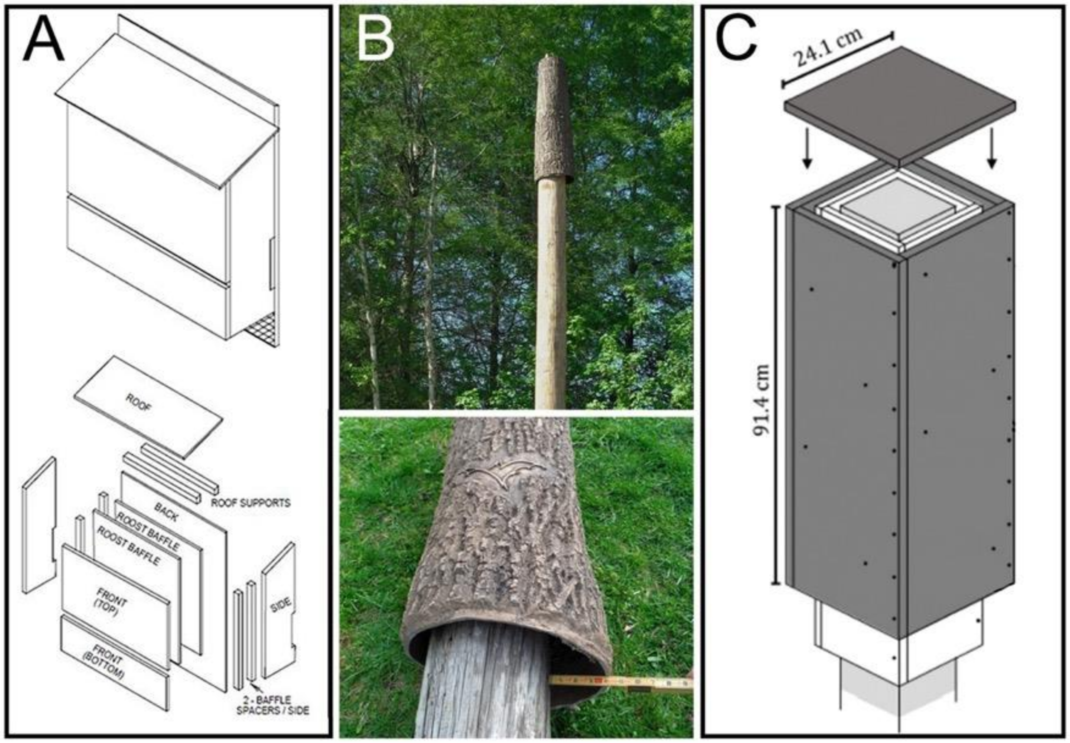

Figure 27. Artificial roost structures for bats. (A) multi-chambered bat box, (B) BrandenBark installed around a utility pole, (C) rocket-box installed around a post. Sources: (A) Guerra (2019), (B) Copperhead Environmental Consulting, copperheadconsulting.com; (C) Tillman et al., 2021.

Multi-chambered bat boxes (Figure 27A) are much flatter than traditional nest boxes to imitate bark crevices. Chambers are located between plywood sheets inside the box (Tillman *et al*., 2021). These bat boxes are the most common roosting structures, and have many variations (Rueegger, 2016). *Rocket-boxes* (Figure 27C) are larger multi-chambered structures that have multiple chambers on each side. The increased length and volume of this design creates a more stable temperature than traditional bat boxes which are prone to overheating (Tillman *et al*., 2021). Many commercial providers of bat boxes recommend painting them black in northern latitudes to absorb solar radiation and make them warmer, and white in southern latitudes to deflect sunlight and keep them cooler (Rueegger, 2016; Guerra, 2019). However, many researchers discourage the practice of painting with dark colors because the risk of overheating is too great (Tuttle *et al*., 2005; Tillman *et al*., 2021). Artificial bark products like BrandenBark (Figure 27B) use various synthetic materials to cast naturalistic sheets of bark that are then wrapped around poles to create crevices (Gumbert *et al*., 2013). Recent research has found that rocket-boxes and BrandenBark are both superior to traditional nest boxes in terms of roosting and brooding success (Martin, 2021).

Many options exist for imitating exfoliating bark in habitat sculpture. Crevices can be carved into material, or sheets of material can be layered and attached to create them. Certain measurements that have been tested in artificial roosting structures may be useful to mimic in sculpted crevices. For instance, Tillman *et al*. (2021) used entrance measurements of 1.9 to 3.8 cm in width, while BrandenBark installation instructions call for a 12.7 cm entrance gap (Copperhead, 2022). The research also indicates that creating habitat sculptures with large thermal masses would be beneficial for bats (Tillman *et al*., 2021). Techniques such as creating artificial bark cast from molds of real bark has enormous artistic potential. Mold making is a commonly employed technique in sculpture, and having custom molds allows sculptors to create hybrid objects that include naturalistic cast elements with more artistic sculpted elements. Adding artificial cast bark or pieces of salvaged bark to sculptures would be an easy way to create naturalistic crevice conditions. Using salvaged bark may be the best option when targeting invertebrates and epiphytic organisms such as mosses and lichens. These organisms have been shown to be extremely responsive to natural features of bark such as chemistry and water retention (Porada & Giordani, 2021; Van Stan *et al*., 2021).

Rock Crevices

The crevices that occur in rock and other hard materials are ecologically important structures that can also be replicated in habitat sculpture. In nature, these crevices create habitat space in cliff faces and rocky outcrops for a group of specialized plants, animals, and other organisms (Lundholm & Richardson, 2010). In human-occupied areas, rock walls, building ledges, and other crevices act as habitat analogs of natural rock crevices (Lundholm, 2011). The plant life of these crevices has been studied extensively, but less so for animals and other organisms (Francis, 2011). Most of the interstitial fauna discussed so far in this section are known to inhabit rock crevices, but there is little research beyond documenting their presence. In general, larger crevices can accumulate larger amounts of organic material and host larger plant species, including trees (Chen *et* al., 2020a). Other dominant plant taxa in these environments include grasses (Poaceae), ferns (Polypodiopsida), vines, bryophytes, and green algae among others (Lundholm, 2011). Bryophytes, lichens, green algae, and cyanobacteria can all grow on hard surfaces, but vascular plants need some form of crevice or cracking to establish and grow. Small cracks in rock walls are thought to be important for plant roots, so sculptures that incorporate crevices should try and replicate these small fractures as well (Chen *et al*., 2020A).

Mineral content in stone and other hard materials can have an effect on which plant assemblages grow and thrive, but this occurs over very long time spans as the material breaks down (Francis, 2011). Just as with mould-filled tree hollows, deposition of leaf litter and other organic debris is a crucial input for these assemblages (Lundholm, 2011). Francis & Hoggart (2012) found that brick walls were significantly higher in species richness compared with other materials because the higher porosity of brick allows for more seed deposition and root development. Concrete has also been found to support a diversity of plant when enough cracks and crevices are present, but its high pH may have a negative effect on plant life (Francis, 2011; Francis & Hoggart, 2012). Concrete and other material mixtures in habitat sculptures can be specially formulated to have hospitable pH values, and potentially other added nutrients (Taylor, 2020). Water is a key limiting resource for lifeforms existing in these small crevices. Patterns of water flow and moisture retention shape biological assemblages in crevice habitats (Chen *et* al., 2020a). Crevices close to the ground retain more moisture and consequently host more vegetation (Francis, 2011). Habitat sculptures can intentionally shape patterns of water flow to create a diversity of conditions. Grooves and channels to direct water flow could also be a powerful visual element that melds artistic and ecological effects.

Studies of rock walls and other rocky analogs focus on the breakdown of materials over time creating crevices where life can take hold, but in habitat sculpture this process can be jumpstarted by intentionally creating crevices. Supplying crevices with organic debris may also accelerate the process since breakdown of rock, cement, and other hard materials typically takes a very long time to occur. Since these crevices are such extreme microclimates, waiting for natural colonization may yield more success than trying to plant certain species. Colonization and growth can be directed by the artist over time, but it may be more fruitful and ecologically interesting to supply the habitat and let nature fill the gaps. More research on the vertebrate and invertebrate species who inhabit these marginal habitat structures is needed, but a sufficient amount of plant life can start an ecological cascade that creates habitat for many other organisms (Sandeep, 2016).

3.1.3 Spatial Levels

As previously discussed, the more physical niches there are in an area, the more ecological niches there will be and the more organisms can coexist in that space (MacArthur, 1958; Stein *et al*., 2014). One way habitat sculptures can create more niches is by creating more complex three-dimensional environments (Pianka, 1966; Loke *et al*., 2015). Sculptures that include multiple forms extending into vertical and horizontal space will create usable surfaces that are separated from each other into niches (Figure 28). This allows multiple organisms to inhabit the same space with less competition between species (*interspecific*) and between individuals of the same species (*intraspecific*) (Morris *et al*., 2016). The terms *habitat complexity*, *habitat heterogeneity*, *structural complexity*, *structural heterogeneity*, *spatial complexity*, and *spatial heterogeneity* can all refer to the diversity of physical forms creating separated niches in a given area (Loke *et al*., 2015). The higher the spatial complexity, the more niche spaces there will be. Pianka (1966) proposed the term *micro-spatial heterogeneity* to describe spatial complexity on the scale of organisms and the structures they interact with, which is the most relevant scale for habitat sculpture installations.

Habitat sculptures that use protruding vertical and horizontal forms will combine bold visual elements with habitat functionality by creating spaces for organisms to carry out various activities like resting, hunting, foraging, communicating, and nesting (Morris *et al*., 2016). Natural habitat structures that provide these separated spaces include tree branches, shrubs, boulders, ridges and rocky outcrops, hillsides, and forest canopies. Artificial analogs of these structures include utility poles, fences, ridges on buildings, and rooftops (Lundholm & Richardson, 2010; Bierregaard *et al*., 2014). Utilizing multiple spatial levels may be especially beneficial for habitat sculptures. The small scale of sculpture installations relative to natural landscape features mean that they must have an increased density of habitat structures and resources to attract and sustain most large organisms.

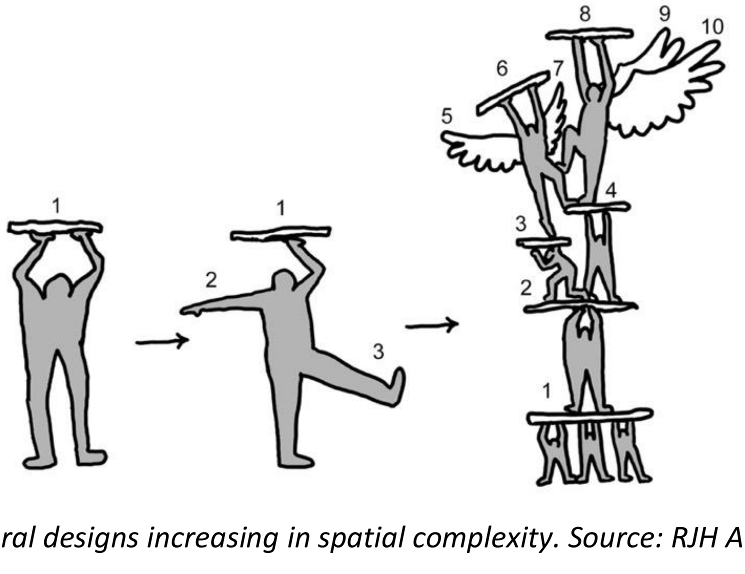

Figure 28. Sculptural designs increasing in spatial complexity. Source: RJH Artworks, 2022.

Vertical Stratification

Tree branches, cliff ledges and other structures in vertical space allow organisms to sit practically right on top of each other without encroachment. The number of vertical levels in an environment is known as *vertical stratification* or *vertical complexity* (Figure 29; Flores *et al*., 2018; Cooper *et al*., 2021). The destruction and conversion of natural habitat structures has led to human-dominated landscapes becoming less vertically stratified, and therefore less suitable as habitat (Loke *et al*., 2015). Artificial habit structures used for creating vertical complexity for conservation purposes include nesting platforms, artificial ground nests, and bird perches (Deng *et al*., 2005; Sherley *et al*., 2012; Vogel *et al*., 2018).

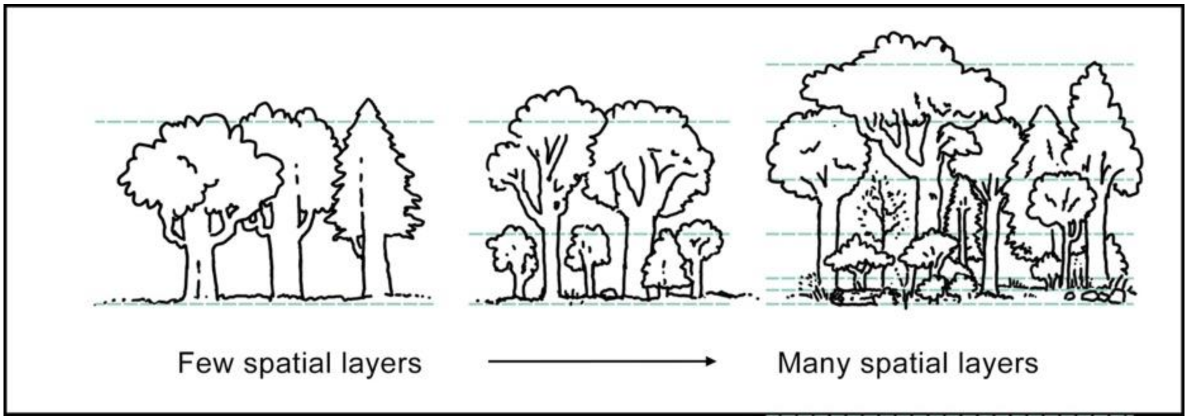

Figure 29. Vertical stratification in forests (top) and in gardens (bottom). Source: RJH Artworks

Nesting Platforms

Artificial nest platforms are made to imitate tree branches, broken-topped trees and snags, and rocky ledges (Hayward, 1994; Deng *et al*., 2005; Rahman *et al*., 2014). In the northeastern USA, nesting platforms are created for large birds such as osprey (*Pandion haliaetus*) and great blue heron (*Ardea herodias*), and smaller birds such as American robin (*Turdus migratorius*) (Bierregaard *et al*., 2014; Cornell, 2022). Platforms are typically made of wood and mounted on trees, poles, and structures like houses and utility lines (Cornell, 2022). Mourning doves (*Zenaida macroura*) will nest in conical wire mesh baskets put in tree branches (Cornell, 2022).

Habitat sculptures can incorporate these forms using a variety of methods. Carving deep ridges into concrete or stone may replicate cliff ledges better than wood platforms. Using salvaged tree parts such as broken tops may also provide naturalistic qualities and visual cues that constructed platforms do not. Lynne Hull's 1994 piece 'Reservoir Tree' serves as a model for how habitat sculptures can utilize these forms (Figure 8). Sculptors can also make use of forms that replicate forks in branches and trunks as possible nesting sites. Including multiple levels of platforms may reduce competition and encourage multi-species assemblages (Schmidt *et al*., 2013; Cooper *et al*., 2021).

Ground nests

Many vertebrates build nests directly on the ground rather than in trees or burrows. These creatures select their nesting sites carefully to avoid predation, which tends to be more prevalent in ground nests than in tree nests (Webb *et al*., 2012). Animals often use vegetative cover over their nests to hide and protect them (Lalas *et* al., 1999; Gates *et al*., 2017). Since the shrubby vegetation used by these animals is often missing in human-occupied areas, nesting site availability may become a limiting factor (Lalas *et* al., 1999). Artificial ground nest shelters have been constructed for conservation purposes and used successfully by multiple species (Sherley *et al*., 2012; Webb *et al*., 2012). These structures simply provide roof-like coverings under which the animals can construct their nests.

Protruding forms near the ground in habitat sculptures can act as cover for ground-nesting animals. Using appropriate plantings around the bases of sculptures may also invite ground-nesters to make use of them by providing more naturalistic cover. Just as with burrow-nesting animals, these structures may not be a good fit for habitat sculptures if ground nesting birds and other creatures are disturbed too often.

Perches

Perches are forms that birds, arboreal mammals, amphibians, and insects use for multiple purposes, including rest, hunting, foraging, and communication (Kaplan, 2021). In nature, tree branches, vegetation, rock faces, and other natural objects that allow organisms to look out for danger are used as perches. Many bird species will readily use human-made objects as such as utility lines and building ledges as perches, but habitat sculptures may be able to attract a wider array of organisms by providing more naturalistic conditions.

The importance of perches for resting is hard to disentangle from other uses, but there is evidence that birds will become stressed and suffer negative health effects without suitable perching sites (Meyers, 1995; Kaplan, 2021). The feet of birds can become wounded if perching on the same form for extended periods. They need variation in size, slope, and texture for healthy perching (Kaplan, 2021). Habitat sculptures would easily be able to provide this level of variation since the forms are individually crafted rather than assembled from standard building materials. Forging metal may be a good way to provide this variation and texture since the thickness and surface texture of forged objects must be intentionally shaped. Casting from molds of natural materials, and using salvaged branches, and carving wood are also methods that could achieve suitable characteristics. Perches should not be smooth or slick since this can cause animals to fall off (Kaplan, 2021).

Perches are used for communication by many different organisms (Schmidt *et al*., 2013). Most people are familiar with birds singing on perches to attract mates and advertise territory, but there is extensive research showing other organisms like crickets (Grylloidea), moths (Lepidoptera), bees (Apoidea), beetles (Coleoptera), frogs (Anura), and many others need perches to vocalize and communicate in the same way (Schmidt *et al*., 2013). Because multiple mating calls can acoustically interfere with each other, many of these creatures seek different spatial level where their calls can stay distinct, thereby increasing their mating chances (Roca & Proulx, 2016). For this function it may be beneficial to provide many perches that are oriented in different directions so animals can divide up the acoustic space in three dimensions. Cooper *et al*. (2014) found that looking at the foraging sites of birds in three dimensions rather than two as has traditionally been done yields a more accurate representation of niche space.

Perches that are used for hunting and foraging are incredibly important habitat structures for birds of prey and insectivores (Asokan & Ali, 2010; Bosler, 2011). The distribution and characteristics of perches for hunting and foraging can have major ecological impacts through predation and competition (Reinert, 1984). If habitat sculpture installations have target organisms that are prey of large predatory birds, the specific characteristics of predatory bird roosts (i.e., heights of 6 m or more) can be excluded (Widén, 1994). Another important ecological effect of perches is the deposition of nutrients and seeds in bird droppings. Artificial perches have been erected in numerous field experiments testing their effects on seed deposition and the resultant regrowth of forests in the vicinity of the perches. Perches generally speed up forest regeneration and increase the abundance and diversity of tree species, although not in all cases (McClanahan & Wolfe, 1993; Carlo & Morales, 2016; Vogel *et al*., 2018). This effect may not be relevant in the short term for habitat sculpture installations that are highly managed and landscaped with specific plants, but in the long term this effect is likely to shape the composition of plant assemblages in installation sites. Relying on spontaneous regrowth from bird droppings could also be an alternative to intensive landscaping and plant management.

Other Spatial Levels

The concept of separate spatial levels has many possible implications for designing physical forms in habitat sculpture; the forms listed above are only a few possible applications. *Horizontal spatial complexity* or *horizontal stratification* was not discussed, but this type of complexity could be achieved by creating wall-like forms that separate horizontal space, or by creating many sculptures spread across an instillation site. The use of forms that protrude into space by spiders (Araneae) for web building was not discussed. This is probably the most common ecological interaction that sculptures have with their surroundings, and there are many interesting forms that could be made to further explore this interaction. The concept of creating multiple levels of soil in containers is also one that has interesting ecological implications and artistic possibilities. Multiple platforms of soil would function in an ecologically similar way to the rock crevices discussed in the last section, but their form for sculpture would be entirely different.

3.1.4 Complex Surfaces

Structurally complex surfaces contain within them all the physical forms discussed so far on a micro-scale. Small pits, crevices, and depressions can shelter organisms and accumulate debris; porous surfaces create interstitial spaces and absorb water; and *surface rugosity* or *surface complexity* creates multiple spatial levels on a micro-scale that separate small organisms and create a more diverse niche space (Torres-Pulliza *et al*., 2020; Van Stan *et al*., 2021). Texture is essentially form on a smaller scale; there is no sharp delineation between the two, which means that many of the lessons and recommendations from larger forms also apply to surface texture. Complex surfaces are highly relevant to ecological communities of tiny flora, fauna, and microbial life (Lundholm, 2011). These microscopic communities support small invertebrate predators and herbivores, who in turn support larger predators on up the food chain (Van Stan *et al*., 2021). The additional structural complexity that moss and lichen growth create on these surfaces makes microclimates and niches for even more invertebrates. By contrast, smooth and uniform surfaces of materials like plastics, metals, polished stone, polished wood, and glass host minimal amounts of life (Torres-Pulliza *et al*., 2020).

Human-made structures that use textured materials like stone, concrete, and brick can act as artificial analogs of naturally complex surfaces (Lundholm, 2011). Under the right moisture and temperature conditions, these artificial surfaces will host moss and lichens, but these assemblages are generally less diverse than natural communities (Lundholm, 2011). By incorporating complex surface structures and textures, habitat sculptures can host and interact with tiny ecological communities in ways that are artistically interesting and ecologically beneficial. These communities are worthy of conservation in their own right, but they also benefit the multi-species assemblages that habitat sculpture seek to create.

For habitat sculpture, the most relevant ecologically active surfaces can be found on bark, decaying wood, and stone (Rose *et al*., 2001; Porada & Giordani, 2021). These structurally complex surfaces are dominated by *epiliths*, meaning organisms that grow on rock, and *epiphytes*, meaning organisms that grow on plants (most often trees; Smith, 1982). Epiliths and epiphytes themselves further increase surface complexity and create a variety of microclimates that host other organisms. The most common epiliths and epiphytes are bryophytes (mosses, liverworts, hornworts), lichens, cyanobacteria, and green algae (Lundholm, 2011; Udawattha, 2018). These vegetative organisms lack the root structures of vascular plants, allowing them to exist on hard surfaces (Morris *et al*., 2016). The lack of root systems also mean that these organisms have special adaptations for collecting and storing moisture from the air (Smith, 1982). The moist microclimates epiliths and epiphytes create are exploited by a variety of organisms from micro-animals like tardigrades (Tardigrada) up to vertebrates like birds and caribou (*Rangifer*) (Russo *et al*., 2020). Microstructure preferences for various surface-dwelling fauna may prove useful for habitat sculpture, but surfaces that accommodate the growth of epiphytes and epiliths will most likely provide far more habitat than meticulously sculpted hard surfaces could.

Experimental Surfaces

Many ecological experiments have been conducted on complex surfaces in the marine environment (Cordell, 2012; Naylor *et al*., 2017; Chapman et al. 2018; O'Shaughnessy *et al*., 2020). This has been inspired by the global decline of coral reefs and the ecological damage wrought by development of waterfronts in human-occupied areas (Firth *et al*., 2014). Waterfronts with structures such as piers and sea walls (known as *armored shorelines*) support fewer marine species because their surfaces are less complex than natural shorelines, thereby providing fewer ecological niches (Morley *et al*., 2012; Chapman et al. 2018).

Experiments on surface complexity typically use test panels that are installed on shorelines and compared to standard seawall panels in terms of the biological diversity and abundance of organisms they host (Figure 30; Cordell 2012; O'Shaughnessy *et al*., 2020). These test panels create complex surfaces using combinations of pitting, cobbling, and grooves. These interventions are generally successful, with different texturing techniques found to attract different organisms (Cordell 2012; Coombes *et al*., 2015). Although this is an extremely active area of research, it is unknown if any findings from marine environments apply to terrestrial environments, and similar research in terrestrial environments is scarce.

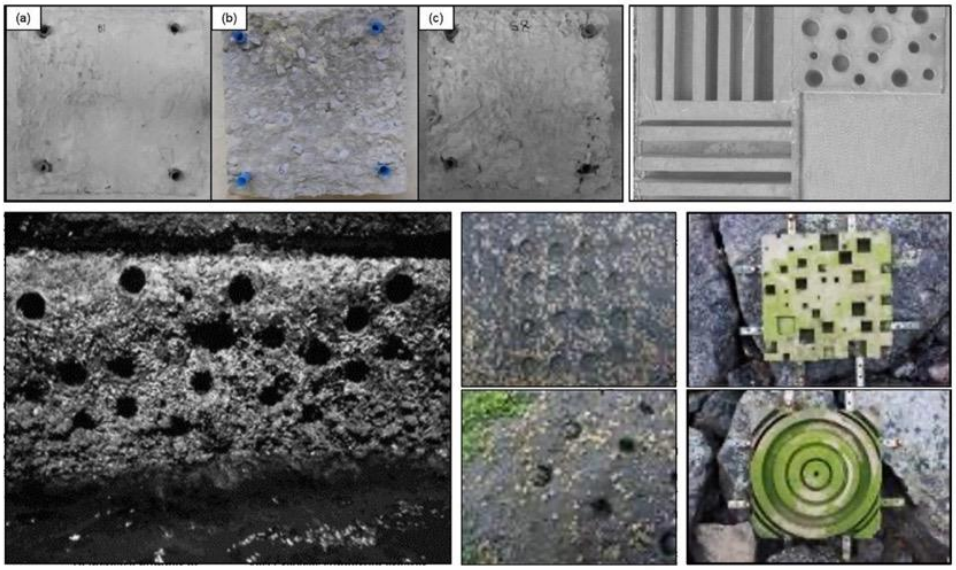

Figure 30. Various test panels comparing different microstructures and levels of complexity. Source: Modified from O'Shaughnessy et al. (2020).

Water Collection

One active area of study that does pertain to surface complexity in terrestrial environments is materials science research into fog harvesting textures (Montàs & Chayaamor-

Heil, 2018). Researchers have been developing surfaces that can collect water from atmospheric moisture in the hopes of addressing water shortages and sustainability issues (Montàs & Chayaamor-Heil, 2018). These surfaces are inspired by *hygroscopic*[5] forms in nature such as the scales of desert-adapted lizards, cactuses, spider silk, beetle cuticles, and leaf venation (Figure 31; Montàs & Chayaamor-Heil, 2018; Qasemi *et al*., 2020; Wan *et al*., 2021). General principles from this research may be able to be applied to sculptural surfaces to create moist microclimates and provide water resources to organisms. Hierarchical groove structures are repeating patterns of grooves of varying depths that are naturally hydroscopic (Figure 32). Carving or casting grooves in these patterns may allow sculptural surfaces to gather water more efficiently, and add significant visual interest (Li *et al*, 2020).

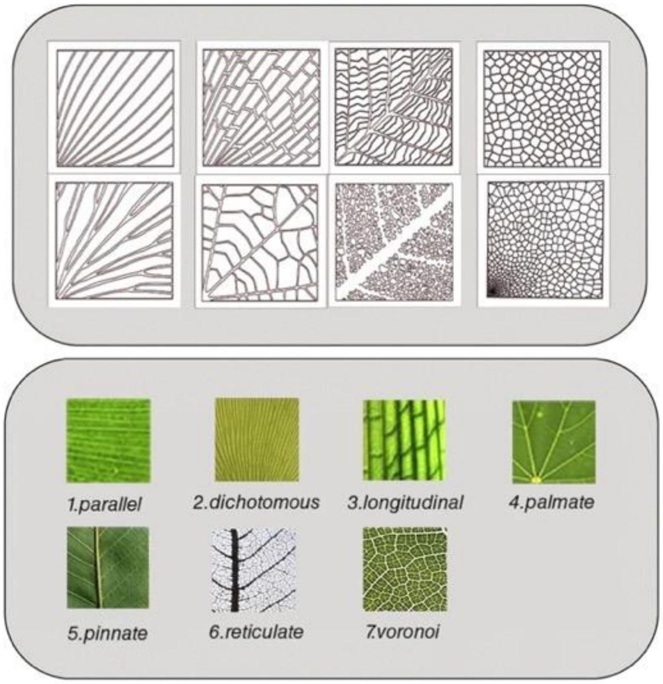

Figure 31. Microstructures mimicking leaf venation. Source: Modified from Qasemi et al. (2020).

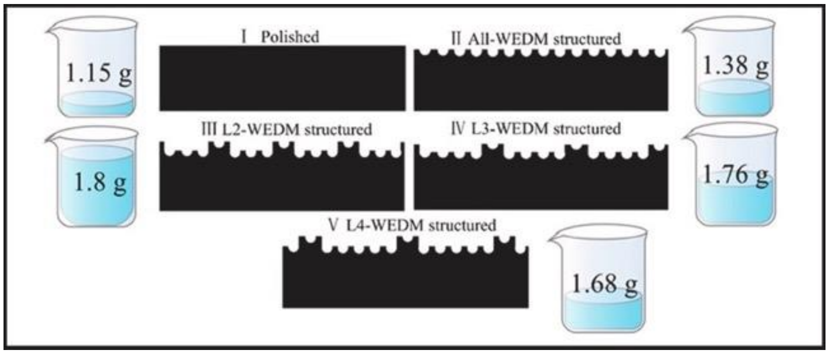

Figure 32. Hierarchical groove structures. Source: Modified from Wan et al. (2021).

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[5] The tendency to absorb water from the atmosphere (Montàs & Chayaamor-Heil, 2018).

Bio Receptive Surfaces

Current research being done into *biological concrete*[6] and other biological building materials could help increase ecological activity on the surfaces of habitat sculptures (Chalcraft, 2013). These materials are meant to encourage bryophyte and fungus growth on their surfaces without compromising structural integrity, a concept known as *bio-receptivity* (Chalcraft, 2013). The critical factors that appear to impact bio-receptivity are porosity, pH, nutrient content, and surface complexity or rugosity (Udawattha *et al*., 2018). As mentioned previously, the porosity of brick allows more water retention, which helps moisture loving bryophytes and fungi. Chairunnisa & Susanto (2018) experimented with different concrete mixtures and found that concrete using crushed brick as an aggregate had good moss-growing properties, probably because of increased porosity. A more complex surface structure also allows water to stay on the material for longer, creating a moister microclimate (Chairunnisa & Susanto, 2018). Different organisms have different pH preferences, but a pH range from 5 to 8 appears to suit the needs of most epiphytic organisms (Chalcraft, 2013; Chairunnisa & Susanto, 2018; Udawattha *et al*., 2018). Material pH can be tested by crushing a sample of dry material and mixing it with distilled water (Udawattha *et al*., 2018). Udawattha *et al*. (2018) tested multiple construction materials and found that clay-based materials like brick, cabook[7], and clay-cement mixtures positively affected moss growth over an 8-week experiment. Along with pH and water retention, they found that organic matter content in the material significantly increased bio-receptivity to moss and other organisms.

Surface complexity alone can generate ecological activity, but paired with bio-receptive materials, the surfaces of habitat sculptures can contribute significantly to their ecological effects. *Woodcrete*, *hempcrete*, and *papercrete* are all custom concrete mixes that replace stone and sand as aggregates with organic materials like wood chips, sawdust, hemp by-products, and recycled paper (Hornby, 2017). Because of their high organic content, these materials should have good properties for creating bio-receptive surfaces on habitat sculptures. Ongoing research into these materials will yield useful information for bio-receptivity, and sculptors can also experiment with custom mixes and materials.

Sculptures can incorporate naturally complex surfaces by using salvaged natural materials such as bark, certain stones, and decaying wood. These objects can have very complex surfaces, and they are likely to possess the beneficial attributes described above for epiliths and epiphytes. Creating molds of natural textures enables many creative possibilities (Figure 33). Rubber molds capture incredible textural detail and are durable enough to replicate complex surfaces. The flexibility of rubber molds also means that they can be stretched and manipulated during casting to create new forms. A natural texture could be stretched out like a skin to cover any sculptural form and create complexity (Figure 34).

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[6] Concrete that supports biological growth on its surface (Chalcraft, 2013).

[7] Cabook is a clay-rich topsoil used as a building material in Sri Lanka (Merriam-Webster).

Figure 33. Cement casts of natural objects with high surface complexity. (Left) cast of a black morel mushroom (Morchella elata); (right) cast of especially furrowed bark with a sculpted figure. The cement used for these casts was modified with sawdust and wood mould to enhance bio-receptivity. Source: RJH Artworks, 2022.

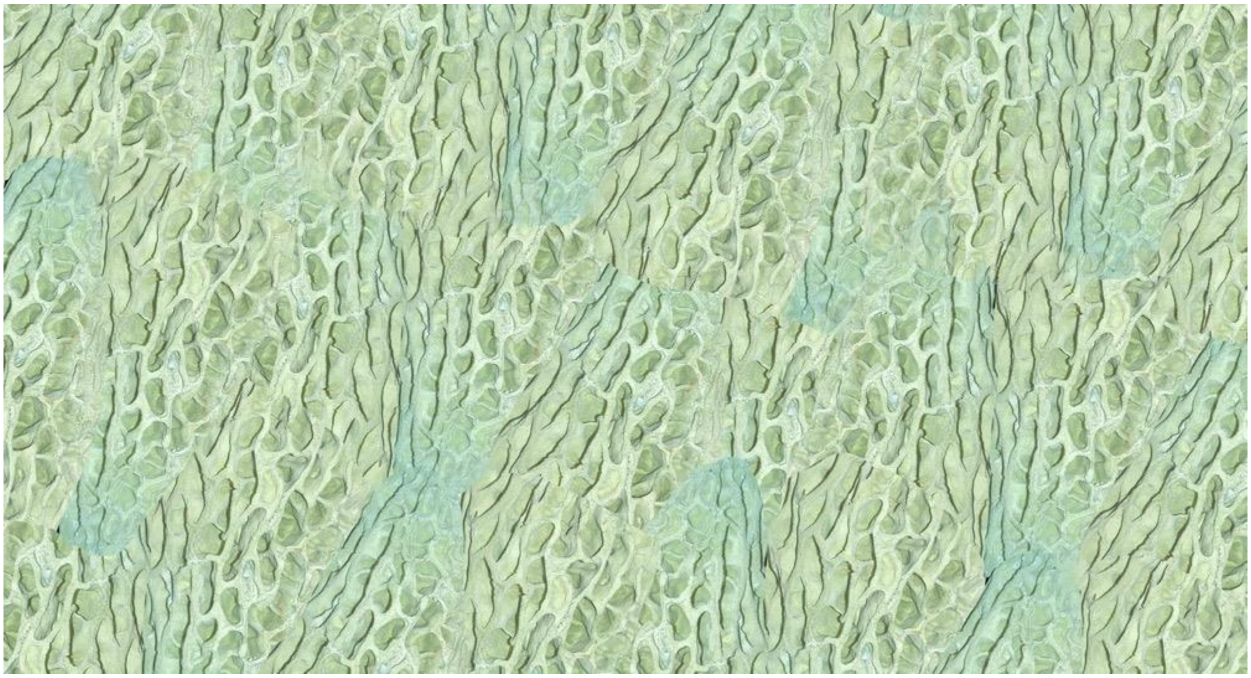

Figure 34. The mold of the morel mushroom above can be stretched out and duplicated to create a textural skin that can be applied to any sculptural form. Source: RJH Artworks, 2022.

Figure 34. A researcher scanning the surface complexity of different building materials. Source: Udawattha et al., 2018.

Three-dimensionally scanning and printing of complex surfaces also holds many exciting artistic possibilities (Figure 34). Replicating surface rugosity and manipulating these surfaces digitally could allow for even more artistic freedom by allowing the artist to scale up or scale down the texture, even creating fractal dimensions of a single form by repeating it at different scales (Torres-Pulliza *et al*., 2020). The most common materials for 3D printing are plastic-based polymers, which might not be suitable for most habitat sculpture applications. Parker *et al.* (2022) were able to 3D print an artificial tree hole in hempcrete, so printing bio-receptive materials is possible, but replication of complex surfaces for terrestrial conservation purposes has not been attempted (Ly *et al*., 2021; Matus *et al*., 2021).

3.2 OTHER PHYSICAL PROPERTIES

3.2.1 Material

Several materials have been discussed at length in the previous sections. These include natural materials like bark, wood in various states of decay, wood mould, organic debris, soil, and stone; and artificial materials such as brick, metal, glass, and various mixtures of concrete. To some degree there is a fundamental conflict between typical sculpture materials and the materials that natural habitat structures are made of. Sculpture materials are meant to withstand decay, but decay is an inexorable process that biological organisms rely on and have adapted to. Decay allows nutrients to cycle from one organism to the next and is often the direct product of biological activity. Most humanmade objects are designed to minimize the amount of decay for safety, utility, convenience, and aesthetics. Importance is also given to the fact that sculptures can outlive their creators. This motivation has driven sculptural material choice from ancient civilization to today.

I have opted for an approach that mixes ephemeral and non-ephemeral materials to balance ecological functionality with longevity and structural integrity, but different artists may approach this balance differently. For instance, some of my sculptures have steel armatures that support the underlying form, but the bulk of the material is organic and is meant to degrade over time (Figure 35). By intentionally allowing decay to occur within a controlled framework, habitat sculptures can engage artistically with dimensions of time and change that traditional static sculptures cannot. For instance, the piece below (Figure 35) is contoured by cement-coated rope so that when the highly decayed (or *veteris*) wood disintegrates, the rope will be left behind showing the outline of the space the figure used to inhabit.

Figure 35. Figure made of highly decayed (or veteris) wood with a steel armature inside. Source: RJH Artworks, 2022

Other important considerations for material choice in habitat sculpture include thermal properties, mineral and nutrient content, permeability and moisture content, anti-microbial properties (e.g., copper-based metals), and texture. Biological interactions between organisms and novel materials should be monitored to ensure there are no clear negative effects, and for further iteration and development. One source of biological risk is sealants, paints, and other coatings that are often applied to metals and other materials, sometimes without the knowledge of the end user. These coatings are chemically formulated to protect materials from corrosion and decay, and therefore can be made from quite toxic compounds. If protection from corrosion and weathering is required, coatings made from natural compounds like shellac and wax-based coatings are unlikely to have harmful biological effects. If toxic compounds and materials need to be employed, ensuring that they do not leach into the environment becomes the highest priority. This can be done by using stable and long-lasting coatings and scheduling regular maintenance to repair or remove coatings that start to chip and degrade.

Sustainable materials have not been discussed so far since they are not directly relevant to how sculpture can create habitat, but there is a clear linkage between the conceptual aim of habitat sculpture and the effects of its materials and construction on the wider environment. The vision of nature and the built environment becoming intertwined and supporting each other is undercut if the sculpture illustrating that vision is actively harming nature. That is also why I have stressed that natural materials and habitat structures used in these projects must only come from salvaged sources. Going out to harvest habitat structures like tree hollows and rock piles that are already limited and under threat would overshadow any ecological benefit that habitat sculptures could provide. Luckily (and very sadly) habitat structures are being removed and destroyed practically every day in any given town or city in the world (Figure 36), so there is no need to take existing ones from natural environments.

Figure 36. Two salvaged tree hollows brought to my studio for use in sculpture. Both were destined for the woodchipper. It can be time consuming and expensive for arborists and landscapers to dispose of tree parts, so they are usually happy to drop off large pieces (left).

Cement Alternatives

The negative environmental impacts of concrete are numerous and considerable. The chemical process of creating the cement in concrete releases a significant amount of CO_2, and the energy required for the manufacturing process overall releases even more (Lehne & Preston, 2018). Environmental degradation from mining and harvesting the sand and gravel used as aggregate in concrete is also immense on its own (Lehne & Preston, 2018). During this research project I reached out to a material scientist named David Stone to procure a carbon-negative concrete alternative they are developing called *Ferrock* (Build Abroad, 2017). I was not able to get a sample batch in time to use for this research project, but the increased tensile strength and other qualities of Ferrock are very exciting, and hold a lot of promise for sculpture work in the future. Cement alternatives may also yield new possibilities in terms of the bio-receptive materials discussed in the last section (3.1.4).

Dead Wood as Sculpture Material

The habitat value of structures and textures associated with trees and dead wood have been discussed extensively, but the material of dead wood itself, independent from its form, has immense ecological value. When wood is used in sculpture it is almost always in an unnatural, sterilized state. Even if it has not been processed or treated, it is kept in a condition that does not allow for the usual explosion of ecological activity that accompanies the natural decay process. One of the major revelations this research project has led me to is that sculptures can be made from rotting, decaying wood, and these sculptures will be inherently teeming with life and ecological interactions. The process of sculpting with decaying wood is much different than working with typical inert wood, but I believe decaying wood can be used and manipulated in habitat sculptures to great effect, both visually and conceptually.

When a tree dies, the chemical defense mechanisms that protected it from being eaten and attacked when it was alive cease to function. The tree's wood then becomes a rich food resource for an astonishing array of saproxylic organisms including fungi, microbes, and arthropods (Stokland *et al*., 2012, Ulyshen, 2018b). These organisms become food for equally numerous groups of fungivores and predators, which in turn become food for larger predators, and so on creating a vast food web based on dead wood (Stokland *et al*., 2012, Ulyshen, 2018b). This ecological activity has consequences for the nutrient cycling of the whole ecosystem, giving the dead wood community an outsized role in ecosystem health and functioning. Saproxylic organisms in mould-filled tree hollows were discussed above, but they are merely a subcategory of the incredible diversity of dead wood specialists (Ulyshen, 2018a). These creatures create unique and fascinating ecological communities that are largely misunderstood and ignored.

Like most natural habitat structures, dead wood is currently under threat from development, forestry, and agricultural (Döös, 2002, Stokland *et al*., 2012). Conservation of dead wood also faces unique challenges stemming from negative cultural attitudes and misconceptions (Brown, 2018). Dead wood is often completely removed in managed landscapes like city parks and residential areas for a variety of factors. A lack of awareness of its ecological value, negative aesthetic attitudes, and safety concerns are widely acknowledged to be the main impediments to dead wood conservation (Ferro, 2018, Horák, 2018, Speight, 1989). These problems become especially pronounced in more heavily populated areas where safety and aesthetic concerns come to dominate all other considerations, and dead wood resources can be virtually non-existent (Horák, 2018).

Although the problem of negative aesthetic attitudes is nearly always mentioned in the scientific literature on dead wood conservation, there have been few efforts to directly address this problem in aesthetic terms (Ferro, 2018; Horák, 2018). Awareness and education can improve attitudes to a certain extent, but this approach does nothing to directly address the problem that people think dead wood is ugly. Until this widely held aesthetic judgment is challenged, the success of dead wood conservation in populated areas will be severely limited. Dead wood is visually dynamic, ever-changing material that as an artist I find fascinating and beautiful. By using dead wood as a central material in sculpture, I aim to highlight its incredible beauty and character, and show what a priceless natural resource it is.

Because dead wood often contains habitat structures such as hollows, mould-filled cavities, small insect cavities, and complex surfaces, it can serve many different habitat functions at once in habitat sculptures. There are many ways to work with dead wood sculpturally because it can take many different forms. The level of decay is the most important factor affecting its material qualities, with veteris wood acting almost more like clay than typical wood. Rather than being carved, highly decayed wood can be molded and bent. Over the course of this research project, I have experimented with using dead wood in plaster mixtures, encasing it in woodcrete, and leaving it relatively intact (Figure 37). Extensive research will be needed to determine the ecological effects of the more extreme modifications but incorporating unmodified dead wood in sculpture is unlikely to affect its value as food and habitat for saproxylic organisms.

Figure 37. Experiments with dead wood as a sculpture material. Source: RJH Artworks, 2022.

3.2.2 Color

Animals use color to navigate their physical surroundings and seek resources (Alonso San Alberto *et al*., 2022). Color is a central component of plant-pollinator interactions, and in animal mating behaviors (Guédot *et al*., 2007; Tedore & Johnsen, 2016). Despite the importance of color in sensory perception, there is very little research on how it interacts with habitat structures. The few cases where color is known to be ecologically relevant to the habitat structures and organisms discussed in this research are in solitary bee and wasp nesting sites (see *Small Cavities* above), mosquito feeding behavior, and thermal effects of light and dark colors via sunlight absorption (see *Exfoliating Bark* above; Tuttle *et al*., 2005; Guédot *et al*., 2007).

Color is one of the most important visual elements of art and design, but there appears to be little synergistic overlap between the culturally mediated emotional role of color in art and its role in ecology. Research has found that most creatures do not respond to color as humans perceive it, but rather to other visual qualities of surfaces such as brightness and contrast (Tedore & Johnsen, 2016). This is true of mosquitos, which are strongly attracted to dark, high-contrast objects (Alonso San Alberto *et al*., 2022). However, olfactory cues will trigger a visual search behavior in certain mosquitos where they become attracted to yellow, orange, and red (the colors of human skin; Alonso San Alberto *et al*., 2022). Although many studies have tried to determine how color mediates habitat selection and behavior in various organisms, no generalizable or particularly useful information has emerged (Tedore & Johnsen, 2016). It seems logical to assume that using naturalistic color would provide more naturalistic visual cues for organisms in general, but there is little empirical evidence to support claim.

Aside from the special consideration that is warranted for color selection in solitary bee and wasp cavities, mosquito attraction, and thermal qualities, it seems that color in habitat sculpture can be freely chosen for artistic effect.

3.2.3 Spatial placement and orientation

Where and how habitat sculptures are placed within installations have important ecological effects that have been described for the habitat structures discussed so far. Amount of sunlight exposure is a critical factor affecting temperature and microclimate conditions, and the angle of sun exposure determined by the orientation also effects these conditions. In the northeastern USA, south-facing objects are warmer, but north-facing objects are more thermally regulated (Coombs et al., 2010). Placement of sculptures relative to prevailing winds can create drier, colder microclimates, or wind blocks can create sheltered pocket that retain moisture and heat. Placement recommendations for specific structures should be at least considered in the creation and installation of habitat sculptures.

It is relatively simple to determine from the literature where the optimal placement is for individual habitat structures or for individual organisms, but the calculus becomes more difficult when there are multiple habitat structures in one sculpture. A sculpture with crevices for bats to roost in should be in full sunlight, but the sculpture might also have small cavities for solitary bees that are best placed in shade. One solution is to have multiple sculptures that each have multiple habitat structures so some cavities and crevices can be in the sun, and some in the shade. Cavity-nesting bee species that prefer hotter conditions may make use of the cavities in the sun, but the majority of species that prefer shade will still be able to use the cavities in the shaded sculpture. Another solution is to intentionally group together habitat structures that have similar placement and orientation requirements. For example, a bat roosting structure could be paired with a cover object for reptiles that also need full sun exposure. Structures can also be in different positions on a sculpture so that one structure faces south while the other one faces north.

Another important consideration for placing sculptures include their proximity to resources like, food, vegetation, and water. This includes important resources in the wider environment outside of the installation site. When possible, sites should be chosen with these resources and conditions in mind. Existing environmental conditions and resources in and around the installation site should also inform the aims of the sculpture. For instance, sites should not be chosen in close proximity to busy roads where car strikes will be likely, but if a site next to a busy road is the only option, then the sculpture should not target highly mobile terrestrial animals like mammals or reptiles.

Proximity to human disturbances is another key consideration for the placement of habitat sculptures. The fundamental conflict between making sculptures that are meant to draw attention and providing habitat to creatures who avoid human presence is a difficult thing to balance. Much of the work that can be done to strike this balance must be done through strategic spatial placement and orientation. Site design can also allow viewers to experience sculptures while maintaining proper distances from sensitive areas.

3.3 ADDITIONAL HABITAT REQUIRMENTS AND RESOURCES

Beyond the sculptural objects themselves, considering the overall site of a habitat sculpture installation reveals opportunities to provide additional resources and elements of habitat so that the sculptures can be ecologically successful. Opportunities will vary widely depending on the site, but whatever space is available should be fully leveraged to provide habitat in concert with the sculptures. Landscaping and gardening can provide water and vegetation resources to take care of basic needs of organisms that cannot be met using sculptural objects. Additional resource inputs like dead wood and direct food supplementation can also be provided, either as temporary measures to jump start ecological processes, or as ongoing measures to maintain conditions that would otherwise deteriorate.

There are few, if any, species that can be sustained in something the size of a sculpture (Quigley, 2011). Even small organisms range far and wide to find the resources and conditions that make up their habitat (Ranius, 2006). Ecologists that study wild populations usually look at large landscape scale factors to understand how organisms and populations function and interact. Sculptures can provide necessary resources for wild organisms in the form of habitat structures, but in order for these structures to be beneficial, the surrounding environment must be able to meet all the other habitat needs of the organisms (Morris *et al*., 2016). Therefore leveraging as large an area as possible to provide habitat elements is absolutely critical for the success of habitat sculptures. Because habitat sculpture installations are targeting environmentally degraded human-occupied areas, the site of the installation has to do a lot of ecological work in a small area. There are many resources for homeowners and enthusiasts for creating 'backyard habitat' from local cooperative extension offices, universities, conservation organizations, and books and articles for general audiences (Tallamy, 2007; Stubbs & Coverstone, 2015; Code, 2019; Majewska & Altizer, 2020). This section will therefore only cover basic principles and how they relate to habitat sculpture installations specifically.

3.3.1 Water

Water is a necessary resource for all living organisms, and natural water sources are severely limited in human-occupied areas. Habitat sculpture installations that include additional water sources will increase their habitability for nearly every conceivable group of target organisms. Concave forms that hold water and forms that create moist microclimates have been discussed as being incorporated into the physical form of habitat sculptures, but the surrounding site provides opportunities to create larger bodies of water such as small ponds, fountains, and even artificial wetlands. There are also opportunities to echo the artificial analogs of water-holding forms that are incorporated in the sculptures with their natural counterparts in the surrounding site. This echoing of features (*i.e.,* having a natural habitat structure and the artificial analog of that structure in the same installation) has benefits for the ecological functionality of the sculptures. For instance, having natural dendrotelmata in proximity to a sculpture that imitates dendrotelmata will facilitate the colonization of the sculptural dendrotelmata and enhance connectivity between the sculpture and surrounding communities.

Natural dendrotelmata and phytotelmata can be hosted in installation sites by planting the tree and plant species that host them. Virtually any tree can develop a dendrotelmata, but certain species develop them at higher rates than other. Beech trees (*Fagus*) are among the species most likely to form dendrotelmata because their thin bark is easily penetrated (Kitching, 2000). Their growth form may also predispose them to forming root and branch pans. In the northeastern USA, American beech (*Fagus grandifolia*) and American sycamore (*Platanus occidentalis*) are good choices for companion plants for habitat sculptures because of their hollow-forming tendencies (Nielsen *et al*., 2007). Like other tree hollows and structural deformities, dendrotelmata mostly occur in very old trees (Travers *et al*., 2018). A management technique called *veteranization* can speed up this process in younger trees and will be discussed further in the next section (3.3.2).

To echo artificial phytotelmata in a sculpture, phytotelmata-hosting plants like pitcher plants can be established. In the northeastern USA, the purple pitcher plant *(Sarracenia purpurea)* is the only habitable pitcher plant. It is capable of hosting at least 165 species of arthropod, bacteria, protist, algae, etc. (Adlassnig *et al*., 2011). The pitcher plant mosquito *(Wyeomyia smithii)* is a non-biting mosquito that is the top predator of the *S. purpurea* food web (Donahue, 2012). If the pitcher plant mosquito is present, then these plants may provide a rare water source that excludes biting mosquitos.

Positioning habitat sculpture next to, or inside of, ponds and other water features will create high moisture conditions that may be extremely valuable habitat. For instance, a sculpture that is mimicking a natural cover object could extend from the edge of a puddle or pond on to dry land, thereby creating a moisture gradient where organisms can find optimal habitat conditions. There are many interesting possibilities for creating habitat sculptures that directly interact with naturalistic water features (Figure 38). Artificial ponds and wetlands will also be very beneficial for sculptures that seek to house amphibians since the aquatic stage of their development is unlikely to occur inside a sculpture. Water features like artificial wetlands can supply the necessary habitat conditions for wetland plants to grow. These plants are essential food sources for various organisms, including some that habitat sculptures may target.

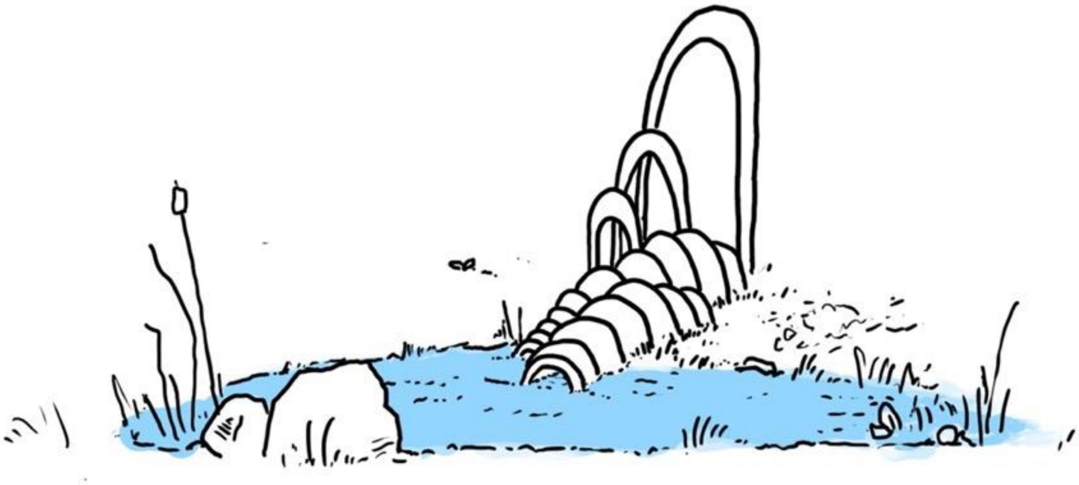

Figure 38. Sketch of a habitat sculpture interacting with a water feature. Source: RJH Artworks, 2022

3.3.2 Plants

Vegetation as food, shelter, and perching space is so ubiquitously needed by so many organisms that habitat sculpture installations essentially need to incorporate plants, and many of them. Even habitat sculpture with as few habitat structures as dozen small cavities for solitary bees and wasps will need to provide a decently sized garden bed for pollen and nectar collection (MacIvor, 2017). Even in the case of saproxylic organisms whose nutritional needs are based on dead wood rather than live vegetation, some insects in their adult forms leave their woody habitat and feed on pollen and nectar (Gimmel & Ferro, 2018). Selecting a site with vegetation in the surrounding area will relieve some of the pressure of provisioning target creatures with enough vegetation, but this will not always be possible when the site is predetermined. As a general rule, the quantity of artificial habitat structures being provided in an installation should not exceed the resources available (Westrich, 1996).

As stated previously about ‘backyard habitats’, resources for planting spaces like residential yards to support biodiversity are plentiful, especially for the northeastern USA (Majewska & Altizer, 2020). Basic advice includes using native plants, minimizing mowed areas, and planting large trees like oaks (*Quercus*) (Tallamy, 2007). Habitat sculpture installations can use this general advice as a starting point for building up plant resources at installation sites, but then they must tailor plant species to match the requirements of the species assemblages and communities being targeted by the sculptures. This is especially crucial for animal species that specialize on one plant or taxon.

Documented relationships between herbivores or pollinators and the plant species that support them can be difficult to find for less studied taxa. The habits and life histories of many insect species remain completely unknown (Ferro *et al*., 2012). If there is little documentation for a species, looking at the preferences and requirements of closely related species and taxa may be the best strategy (Tallamy, 2007). General advice for wildlife gardening is the best fallback in cases where so little is known that plant species can’t be chosen to support specific target species.

Direct interactions between sculptures and plants can be visually and conceptually powerful and can yield benefits for plant growth and ecological functionality. In the examples below (Figure 39), sculptures serve as lattices for climbing vines, and the vines provides connectivity for insect to access the sculptures. Vines growing on sculptures can create microclimate variation through shading and may attract certain species to the sculptures.

Echoing sculptural habitat structures like solitary bee and wasp cavities with plants that leave behind hollow reeds and stems will have benefits for colonization and landscape connectivity as described above (section 3.3.1). This may be especially beneficial for this particular habitat structure since cavity-nesting bees and wasps will sometimes rear multiple broods in single season. Making sure cavities are not limited will increase population size (MacIvor, 2017).

Figure 39. Two sculptures at the DGC Permasculpture Garden. (Left) a common hops vine (Humulus lupulus) climbs a steel structure, (right) grapevine (Vitis sp.) surround but mostly avoid a structure made of copper pipes. Source: RJH Artworks, 2021.

As with dendrotelmata, trees can be planted to provide habitat structures like tree hollows that will echo the artificial habitat structures used in the sculptures. Since these structures can take over 100 years to develop, veteranization of young trees can provide these habitat structures in the short term (Sebek *et al*., 2013; Bengtsson & Wheater, 2021). Veteranization includes things like inoculating trees with heart-rot fungi and other wood deteriorating organisms, killing trees by *ringbarking* or *topping*, breaking branches, removing large section of bark, and carving artificial hollows using a chainsaw (Sebek *et al*., 2013; Bengtsson & Wheater, 2021).

3.3.3 Dead wood

Adding unmodified dead wood to an instillation site can provide a rich source of nutrients for plants, fungi, microbes, and animals. If dead wood is being used in a sculpture, then placing unmodified dead wood (i.e., rotting logs, snags) in and around sculpture will facilitate colonization and create connectivity between the sculpture and natural populations of saproxylic organisms. Even if no saproxylic creatures are being targeted in the sculpture installation, dead wood can be used as a food and shelter resource by many generalist and facultative creatures (Stokland *et al*., 2012). The many species of fungi that inhabit dead wood can also add visual interest to a landscape that is dominated by vegetation (Figure 40).

Figure 40. Fungi and moss on dead wood. Source: RJH Artworks, 2019.

3.4 SCULPTURAL PROTECTION OF EXISTING HABITAT STRUCTURES

Another way that sculpture can increase the habitat potential of human-occupied areas is to protect habitat structures and resources that already exist. This is a different method than the technique described above of using salvaged habitat structures as parts in sculptures. When using salvaged habitat structures there is some degree of modification that happens, whether minimal or extreme. Salvaged structures are also taken from their environments and moved to new locations, potentially with very different biological and microclimatic conditions. These structures begin a new life ecologically when they are taken and incorporated into habitat sculpture installations. In contrast, *sculptural protection* of habitat structures entails keeping structures where they are and erecting sculpture installations around them (Figure 41). This strategy has many benefits, including a higher likelihood of ecological activity than other methods, the ability to physically protect habitats from destruction, and a strong conceptual message about the value of natural habitat structures.

The methods discussed so far have been focused on creating new habitat structures in developed areas where they are lacking. But developed areas also contain remnant fragments of natural landscapes that have survived and continue to function (Niemelä *et al*., 2011). These remnant structures become increasingly valuable to non-human organisms as development chips away at more and more of their habitat (Horák, 2018). By using habitat structures that are already enmeshed in ecological activity, habitat sculptures will have a much better chance of interacting with non-human organisms in visually and conceptually interesting ways. Making habitat structures from scratch has no guarantee of success in attracting and sustaining target organisms and communities. Sculptural protection of habitat structures at minimum will benefit the organisms that already rely on those structures by ensuring their continued existence.

Remnant habitat structures in developed areas sustain fragile links to surrounding natural ecosystems, benefiting the health and wellbeing of residents (WHO, 2016; Cox *et al*., 2017). Sometimes these natural structures are valued and protected, but more often than not they face inevitable removal at the hands of developers and property owners. Sculptures can provide physical protection for these threatened structures, ideally backed up by community groups and residents who were involved with their creation and installation. Sculptures can also physically stabilize natural structures such as snags, thereby alleviating safety concerns that might lead to their removal (Figure 41). The fear of snags falling and causing property damage or injury is one of the most common reasons that they are removed and destroyed in populated areas, even though pollarding[8] and stabilization have been shown to be effective solutions (Ferro, 2018).

Figure 41. Ideas for sculptural protection of snags in urban environments (left) and in suburban/rural environment (right). Source: RJH Artworks, 2022

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[8] Pollarding is the technique of cutting branches from standing trees for firewood or for safety (Ferro, 2018).

Figure 42. Sculptural protection of a snake refugia. Source: RJH Artworks, 2020

No matter what the proximate cause of their removal and destruction, habitat structures are ultimately not maintained or protected because people don't care about them. This could be because they aren't aware of their ecological importance, or because they think them unsightly, or they are indifferent for any number of reasons. Large-scale sculptures that draw attention and protect habitat structures send a clear message that these objects are valuable and worthy of care. Using precious materials and symbolic imagery to indicate sacredness is one strategy I have explored in designs to make an explicit statement of importance and emotional investment (Figure 41, left). This signifier of social and emotional importance is probably a greater source of protection than the physical protection provided the sculpture itself. My aim is that these installations inspire curiosity and learning about habitat structures, eventually changing attitudes that effect how other habitat structures are treated.

By highlighting and celebrating nature that exists in developed areas, I also hope to convey that these habitats are no less important and beautiful than their counterparts out in the wilderness. The attitude that nature in the human-dominated landscape is inherently less valuable allows people to act without regard for their local impacts, further degrading ecosystems worldwide. If these sculptures can play a small part in opening people's eyes to the natural beauty all around them, then they will have been successful.

4. SCULPTURE INSTALLATIONS CREATED

During this research project I created multiple sculptures to explore methods for habitat creation. This exploration led me to useful discoveries, such as the abundance of habitat structures that are available for salvage and the unique materiality of sculpting dead wood. My aim was to install the sculptures in their respective sites and record the results in terms of ecological interactions or lack thereof. There was not time to carry out these observations during this project, but this provides a clear direction for future work, perhaps in collaboration with ecology and biology researchers. There are still many techniques to explore and lessons to be learned, but these finished pieces and works-in-progress demonstrate the artistic possibilities inherent in the habitat sculpture approach.

The pieces created include a large sculpture installation called *Saproxylic Food Web* located on the campus of the College of the Atlantic; and multiple sculptures created for a 'permasculpture garden' in downtown Ellsworth, Maine. I will also discuss plans for future work including a habitat sculpture installation on the Schuylkill River Trail in Philadelphia, Pennsylvania, and a sculptural earthbag structure at Sweet Pea's Farm in Bar Harbor, Maine.

4.1 SAPROXYLIC FOOD WEB

4.1.1 Planning Process

Saproxylic Food Web is a habitat sculpture installation located in front of the Dorr Museum of Natural History on the College of the Atlantic campus in Bar Harbor, Maine. The sculpture was conceived of in conversations with the director of the Dorr Museum, Carrie Graham. While discussing ideas for sculptures that protect standing dead trees (Figure 41), Carrie suggested that one of these sculptures could be installed at the museum and could be used as an education tool to teach students and visitors about the ecology of dead wood. As we were making initial plans for the installation (Figure 43), the museum grounds were being re-landscaped to improve ADA compliance, and a perfect opportunity presented itself. An old scotch pine tree (*Pinus sylvestris*) located next to the museum entrance had to have half of its roots severed, killing the tree. The original plan called for the tree to be disposed of in a woodchipper, but the landscapers agreed to leave the newly deceased snag in place for me to use as the centerpiece of the sculpture installation (Figure 44). Protecting this valuable habitat structure will benefit the surrounding ecosystem by hosting countless saproxylic organisms.

The sculpture itself consists of large steel spirals surrounding the snag, physically and metaphorically protecting it. Brightly colored steel sculptures are attached to the spirals depicting the saproxylic organisms who will eventually inhabit the tree. There are over 120 organisms depicted, allowing viewers to visually absorb the vast diversity of the saproxylic ecosystem. The artistic interaction of wild organisms being seen next to enlarged, colorful sculptures of themselves is what makes this piece conceptually compelling to me. This conceptual basis creates a synergistic interaction between the artistic and ecological features of the piece. The sculpture ensures the ongoing existence of this saproxylic community, and the saproxylic organisms inhabiting the sculpture support the artistic concept of the piece.

Figure 43. Initial sketches of the 'Saproxylic Food Web' concept. Placement in the spiral roughly corresponds to a creature's trophic level in the dead wood food web. This visually shows how the creatures higher up depend on the creatures below them. Source: RJH Artworks, 2020

Figure 44. (Left) the snag created by the new landscaping plan for the museum grounds. (Right) a digital illustration of the 'Saproxylic Food Web' installation, including new plantings. Source: RJH Artworks, 2021

The sculpture itself does not attempt to create artificial habitat using the techniques described in sections 3.1 and 3.2; rather, it leaves the heavy lifting of sustaining ecological activity to the *Pinus sylvestris* snag, as described in section 3.4. The ecological advantages of this approach have been discussed, but in the case of this piece I also felt that creating *artificial* habitat through sculpture would have been visually and conceptually distracting. The piece is meant to celebrate the beauty of dead wood and educate the public about its ecological importance. Making the physical form of the sculpture perform additional duties like creating cavity-nests or water basins would only serve to take attention away from the dead tree and the saproxylic organisms that are depicted around it.

The installation does, however, make extensive use of the habitat creation and supplementation techniques described in section 3.3. A bed of native flowers, shrubs, and ground covers surround the sculpture, replacing the turf grass that had been there (Figure 45). Plantings were chosen to support saproxylic organisms likely to inhabit the installation (Table 2). In researching these organisms, I found flower longhorn beetles (Cerambycidae) and saproxylic bees and wasps (Hymenoptera) to have the most intensive vegetative resource requirements, so plantings were chosen accordingly.

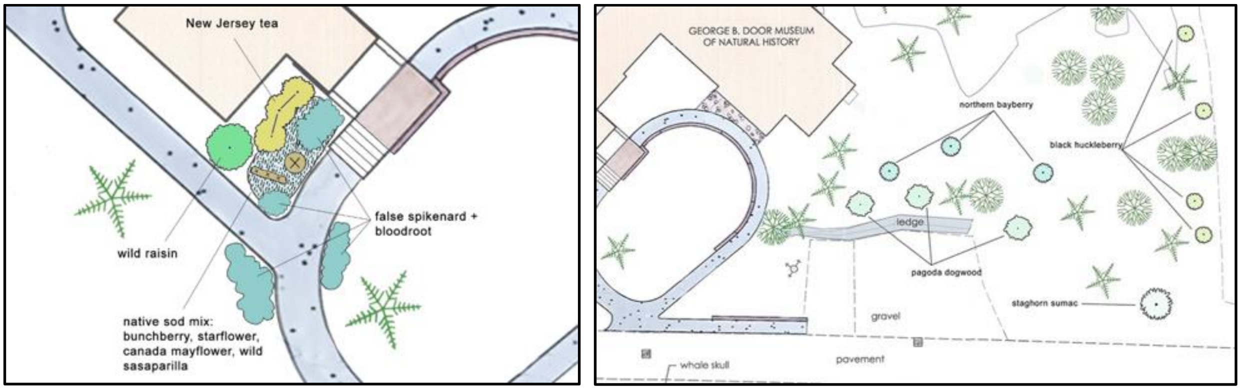
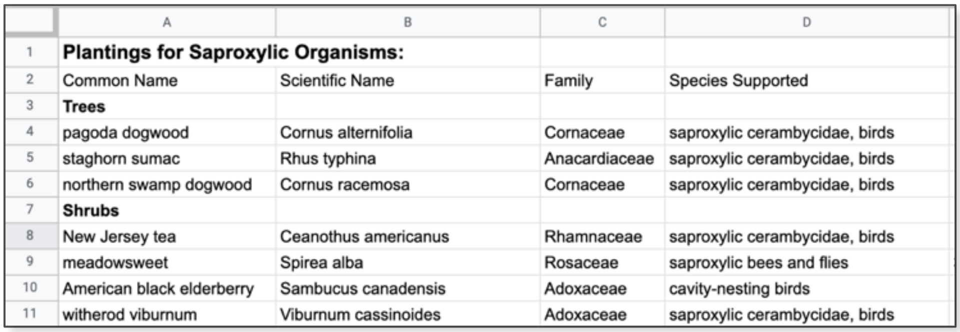


Figure 45. (Left) plantings in the immediate vicinity of the sculpture, (right) larger plantings spread out over the museum grounds. I collaborated with COA undergrads Lauren Brady and Alexander Percy to come up with the landscape design and plant selection shown here.

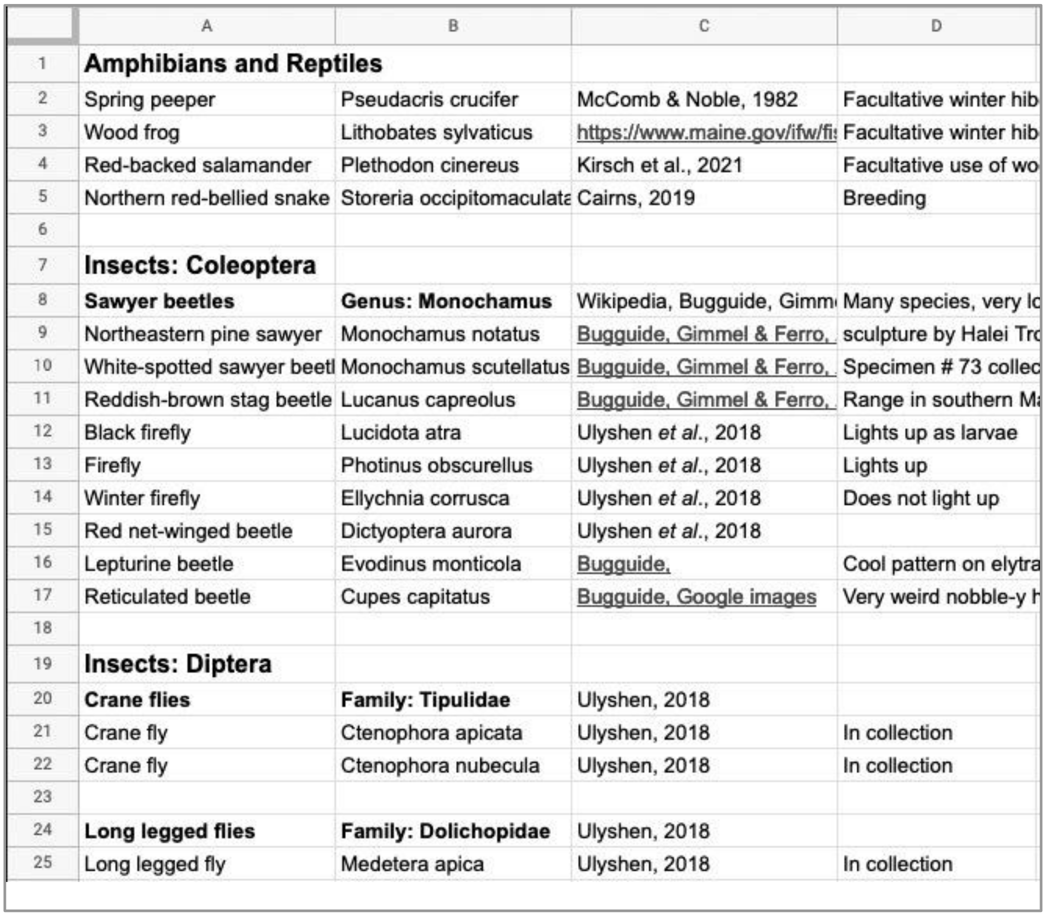


	A	B	C	D
1	**Plantings for Saproxylic Organisms:**			
2	Common Name	Scientific Name	Family	Species Supported
3	**Trees**			
4	pagoda dogwood	Cornus alternifolia	Cornaceae	saproxylic cerambycidae, birds
5	staghorn sumac	Rhus typhina	Anacardiaceae	saproxylic cerambycidae, birds
6	northern swamp dogwood	Cornus racemosa	Cornaceae	saproxylic cerambycidae, birds
7	**Shrubs**			
8	New Jersey tea	Ceanothus americanus	Rhamnaceae	saproxylic cerambycidae, birds
9	meadowsweet	Spirea alba	Rosaceae	saproxylic bees and flies
10	American black elderberry	Sambucus canadensis	Adoxaceae	cavity-nesting birds
11	witherod viburnum	Viburnum cassinoides	Adoxaceae	saproxylic cerambycidae, birds

Table 2. Sample of spreadsheet used to document saproxylic species associations and choose plants for the installation.

Larger plants that my research indicated are the most common host plants of saproxylic Cerambycidae, Hymenoptera, and cavity-nesting birds are spread out over the museum grounds (Figure 45; Strauss, 1991). These plantings extend from the museum into an adjacent wooded lot with dead wood resources, thereby enhancing landscape connectivity. The installation also makes use of water supplementation and artificial tree hollow and cavity-nest creation (Figure 46). These artificial habitat features are not made to be sculptural, but rather to blend in with the snag and surrounding landscape for the reasons stated above regarding the conceptual focus of the piece. Three large tree hollows were carved into the snag; two sheltered from the rain to be used as nest cavities, and one exposed to the rain to create a dendrotelmata. One of the dry cavities was filled with wood mould taken from a salvaged tree nearby to create a wood mould hollow for specialized saproxylic invertebrates (Hilszczański *et al*., 2014). Each of the hollows has different dimensions to appeal to a range of cavity-nesting organisms (Figure 46).

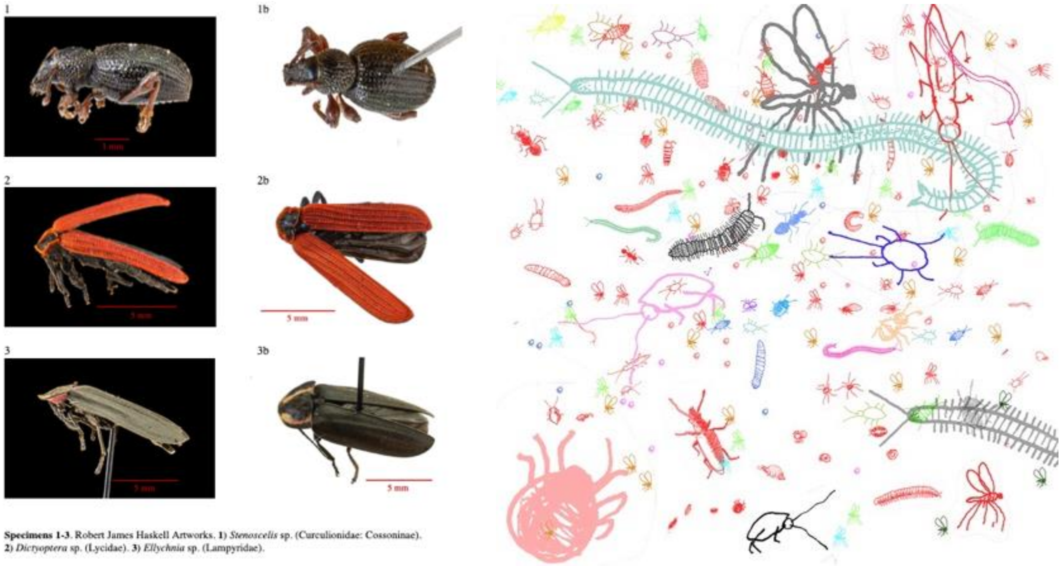
Figure 46. Ethan Miller carving a chainsaw hollow into the snag using 'plunge cuts' as described in Griffiths et al.*, 2018.*



	A	B	C	D
1	**Amphibians and Reptiles**			
2	Spring peeper	Pseudacris crucifer	McComb & Noble, 1982	Facultative winter hib
3	Wood frog	Lithobates sylvaticus	https://www.maine.gov/ifw/fi	Facultative winter hib
4	Red-backed salamander	Plethodon cinereus	Kirsch et al., 2021	Facultative use of wo
5	Northern red-bellied snake	Storeria occipitomaculata	Cairns, 2019	Breeding
6				
7	**Insects: Coleoptera**			
8	**Sawyer beetles**	**Genus: Monochamus**	Wikipedia, Bugguide, Gimm	Many species, very lo
9	Northeastern pine sawyer	Monochamus notatus	Bugguide, Gimmel & Ferro,	sculpture by Halei Tro
10	White-spotted sawyer beetl	Monochamus scutellatus	Bugguide, Gimmel & Ferro,	Specimen # 73 collec
11	Reddish-brown stag beetle	Lucanus capreolus	Bugguide, Gimmel & Ferro,	Range in southern M
12	Black firefly	Lucidota atra	Ulyshen *et al.*, 2018	Lights up as larvae
13	Firefly	Photinus obscurellus	Ulyshen *et al.*, 2018	Lights up
14	Winter firefly	Ellychnia corrusca	Ulyshen *et al.*, 2018	Does not light up
15	Red net-winged beetle	Dictyoptera aurora	Ulyshen *et al.*, 2018	
16	Lepturine beetle	Evodinus monticola	Bugguide,	Cool pattern on elytra
17	Reticulated beetle	Cupes capitatus	Bugguide, Google images	Very weird nobble-y h
18				
19	**Insects: Diptera**			
20	**Crane flies**	**Family: Tipulidae**	Ulyshen, 2018	
21	Crane fly	Ctenophora apicata	Ulyshen, 2018	In collection
22	Crane fly	Ctenophora nubecula	Ulyshen, 2018	In collection
23				
24	**Long legged flies**	**Family: Dolichopidae**	Ulyshen, 2018	
25	Long legged fly	Medetera apica	Ulyshen, 2018	In collection

Table 3. Sample of spreadsheet listing saproxylic species likely to be present in Downeast Maine.

The conceptual basis of the installation requires that the steel sculptures depict saproxylic organisms that are native to the region of Downeast Maine. This ensures that there is a chance of juxtaposition between the organisms and their sculptural likenesses. No region-specific catalogue of saproxylic organisms and facultative dead wood users exists, so I had to do extensive research to compile one (Figure 47). Scientific literature or documentation of any kind regarding saproxylic organisms was extremely sparce for the broader region, and completely nonexistent for Downeast Maine specifically. To compile a species list, I looked at broader regional inventories (e.g., North American species, Canadian maritime species) and deduced from range maps and anecdotal reports which species were likely to be present at the installation site (Majka, 2007; Ferro *et al*., 2012; Ulyshen, 2018a). I also collected insects over a two-year period to identify local saproxylic species that may have not been mentioned in the literature (Figure 48). Systematic surveys of dead wood habitats were carried out in the spring of 2020 with guidance from Carrie Graham and Susan Letcher. This research was a valuable way to get a sense of the composition of typically dead wood assemblages in the area. It allowed me the opportunity to personally see saproxylic insects moving and interacting in ways that are typically hidden from view.



Specimens 1-3. Robert James Haskell Artworks. **1)** *Stenoscelis* sp. (Curculionidae: Cossoninae). **2)** *Dictyoptera* sp. (Lycidae). **3)** *Ellychnia* sp. (Lampyridae).

Figure 48. Saproxylic insect surveys. (Left) specimen photographs and species identification, (right) illustrations of saproxylic species observed in the study. Source: RJH Artworks, 2022

4.1.2 Fabrication and Assembly

After the surveys and species lists were completed, I began fabrication of the saproxylic sculptures in the fall of 2020 with help from COA undergraduate students. The project was funded by the firm Design Group Collaborative and the Dorr Museum. To visually highlight the diversity of creatures in the saproxylic food web, I wanted the sculptured creatures to be a jumble of different colors, sizes, and styles. I reached out to the COA community to see if students wanted to contribute their own saproxylic sculptures so that there would be multiple visual styles, and I also wanted to see if this type of community involvement could be done in future projects, and how to best go about it. Students worked with me in my metalworking studio over the winter of 2020-2021 to fabricate multiple steel sculptures (Figure 49-52).

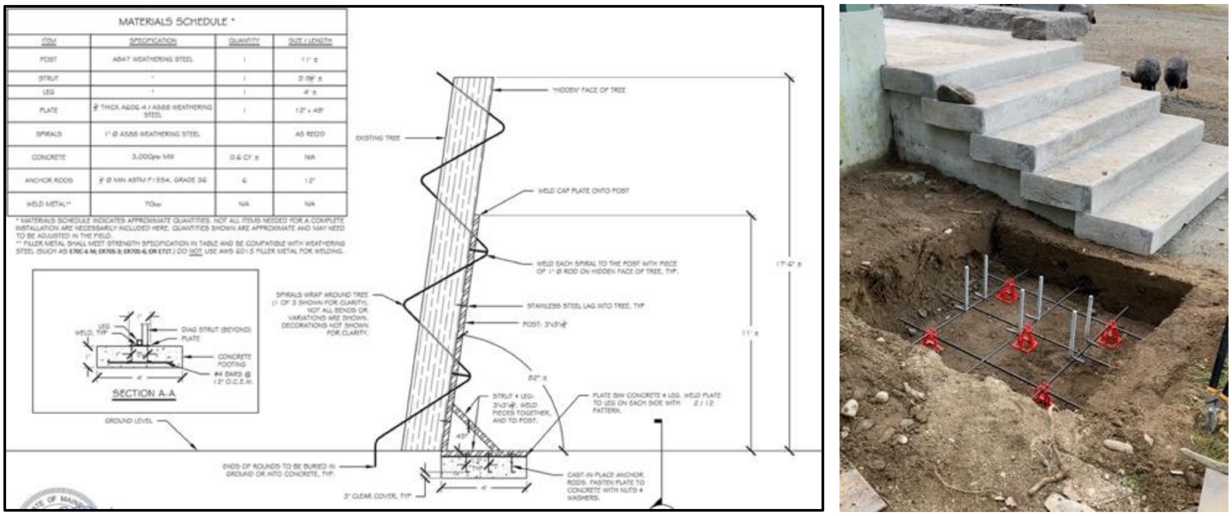
Figure 49. College of the Atlantic students forging steel for sculptures.

Figure 50. Students chose which saproxylic creatures they wanted to create and came up with designs for them. I then advised them on how to best go about the fabrication process in steel.

Figure 51. Student work in progress. (Left) Eli Johnson's creates a lepturine beetle (Evodinus monticola); (center) Westly Reason creates a spring peeper (Pseudacris crucifer); (right) Mark Francis collaborates with me on a moss mite (Oribatida) and a fungus gnat (Sciaridae).

Figure 52. Plasma-cut steel sculptures. Made with help from illustrator Josh Worden.

After the students finished their sculptures, I began making simple steel creatures cut out of sheet metal with a plasma torch (Figure 52). To create the visually overwhelming aesthetic I envisioned as being a metaphor for enormity of saproxylic diversity, I needed a lot of creatures to completely fill the space. I collaborated with a local illustrator and good friend Josh Worden to illustrate over 100 creatures from my species for plasma cutting. After the creatures were finished, I began work on the large steel spirals that the creatures attach to. I chose 1" thick weathering steel for the spirals because of their durability, and for the brown rust-like patina that forms when they are exposed to moisture. I consulted with local firm Hedefine Engineering to create a support structure for the spirals so they would not rely on the snag for support (Figure 53). In future projects I hope to design these support structures so they can fully support snags that are at risk of falling.



MATERIALS SCHEDULE *

ITEM	SPECIFICATION	QUANTITY	SIZE / LENGTH
POST	A847 WEATHERING STEEL	1	11' ±
STRUT	"	1	3'-9" ±
LEG	"	1	4' ±
PLATE	⅜" THICK A606-4 / A588 WEATHERING STEEL	1	12" x 48"
SPIRALS	1" Ø A588 WEATHERING STEEL		AS REQ'D
CONCRETE	3,000psi MIX	0.6 CY ±	N/A
ANCHOR RODS	⅝" Ø MIN ASTM F1554, GRADE 36	6	12"
WELD METAL**	70ksi	N/A	N/A

* MATERIALS SCHEDULE INDICATES APPROXIMATE QUANTITIES. NOT ALL ITEMS NEEDED FOR A COMPLETE INSTALLATION ARE NECESSARILY INCLUDED HERE. QUANTITIES SHOWN ARE APPROXIMATE AND MAY NEED TO BE ADJUSTED IN THE FIELD.

** FILLER METAL SHALL MEET STRENGTH SPECIFICATION IN TABLE AND BE COMPATIBLE WITH WEATHERING STEEL (SUCH AS E70C-6 M; ER70S-2; ER70S-6; OR E71T.) DO NOT USE AWS E015 FILLER METAL FOR WELDING.

Figure 53. Support brace with concrete footer designed by Hedefine Engineering.

Figure 54. Pouring the concrete pad, installing the support brace, and bending the steel spirals.

Figure 55. Installing the spirals around the snag with my work crew of volunteers. The spirals were welded to the support base near the bottom and attached to the tree near the top.

Figure 56. (Left) the finished spirals, (right) the first few creatures installed on the spirals. Source: RJH Artworks, 2022

The steel rods were heated with torches and forges and run through a Hossfeld Bender to achieve an organic spiraling form (Figure 54). The spirals were brought from my metalworking studio to the site and installed over the fall of 2021 (Figure 55). The organism sculptures were painted with a durable two-part epoxy paint (Macropoxy 646) to resist corrosion and minimize the risk of paint chipping and contaminating the environment. The attachment mechanisms for the sculptures allow them to be easily taken down and repaired or replaced in case of paint chipping or structural failures.

Saproxylic Food Web was completed in the spring of 2022. Plantings will continue to be developed over the summer, and an exhibition for this piece will be held at the Dorr Museum in the fall. The opening for the exhibition will be hosted in front of the museum where the installation will be accompanied by several large format photographs displayed on the courtyard walls (Figure 57). These photographs are part of temporary sculpture installations where bronze and gold spheres enclose dead wood resources in the nearby forest. These photographs are meant to show the natural beauty of dead decaying wood, and convey a sense of reverence and value by encircling them with precious metals. During the exhibition these bronze spheres will be temporarily installed on pieces of dead wood around the COA campus. This will draw a direct connection between the beautiful decaying structures in the photographs and the same beautiful structures that exist all around us. I hope that this will open some people's eyes to the beauty of dead wood the way that mine have been over the past few years. While these bronze and gold structures will be temporary, the installation

Figure 57. Sculptural protection of dead wood resources with bronze spheres. Source: RJH Artworks, 2022

4.1.3 Artist Statement

This sculpture celebrates the vibrant and diverse community of saproxylic organisms which is so often misunderstood or ignored. Saproxylic creatures are fascinating in their own right, but they are also crucial for healthy ecosystems. They rapidly turn dead trees into rich soil, they provide nesting cavities for small birds and mammals, and they feed predators higher on the food chain like woodpeckers and black bears. People tend to reflexively remove and destroy dead wood wherever they can find it, leading to declines in biodiversity and ecosystem functioning. Many saproxylic animals are threatened with extinction thanks to these practices. It is essential for their survival that we keep fallen logs and standing dead trees like this one intact and protected wherever we can. I hope this sculpture highlights the beauty of dead wood and shows what a priceless natural resource it is. Thanks to Eli Johnson, Gabriella Bzezinski, Halei Trowbridge, Liv Durham, Mark Francis, Micah Lindberg, Michelle Hanselowski, Minu Toos, Truth Muller, and Westly Reason for contributing their animal sculptures to the installation.

Figure 58. 'Saproxylic Food Web', 2022 (in progress). Source: RJH Artworks, 2022

Figure 59. 'Saproxylic Food Web' (detail). Source: RJH Artworks, 2022.

Figure 60. 'Saproxylic Food Web' (detail). Source: RJH Artworks, 2022.

4.2 DGC PERMASCULPTURE GARDEN

In this installation site I was able to experiment with different habitat sculpture techniques without having an overriding conceptual theme. Many of the sculptures planned for this site are still in development at the time of writing, but they are still illustrative of methods and techniques that can be used for habitat creation in sculpture. Unlike the *Saproxylic Food Web* installation, the pieces in the DGC Permasculpture Garden are focused on creation of artificial habitat structures rather than protection of existing habitat. This site did not have much in the way of habitat structures or resources to start, so these had to be created and built up over time. The following is a brief discussion of the site and how the sculptures that have been created so far use the artificial habitat creation methods discussed in this research.

4.2.1 Background

The DGC Permasculpture Garden is a collaboration with the architecture firm Design Group Collaborative (DGC). In 2013, DGC purchased an office space in downtown Ellsworth, Maine. The grounds outside the office had been a turf lawn, but lack of upkeep and an exposed microclimate left the grass sparce and the ground dried and cracked. The property was also surrounded by large colony of the aggressively invasive plant Japanese knotweed (*Reynoutria japonica*). The owners wanted to improve the site, and I proposed that we turn the lawn into an ecological sculpture garden, or *permasculpture* garden. Using concepts and techniques from permaculture and wildlife gardens, we developed a plan to restore the site to ecological functionality. This consisted of returning nutrients and organic matter to the soil over several years, building a garden, and installing ecological sculptures that would intertwine themselves with the plants and wildlife. Soil improvement and knotweed control began in 2015. By the time this research project began, the site had been transformed into a healthy landscape full of native plants, setting the stage for habitat sculptures to be created and installed.

DGC is an environmentally conscious firm, but they have found that most clients have to be cajoled into making environmentally friendly choices with their buildings and landscapes. DGC's hope is that clients who come to their office will encounter a living landscape buzzing with ecological activity, hopefully getting them interested in pursuing a similar path.

4.2.2 Biophilic Cityscape

This installation consists of several sculptures, most of which are still in progress. The concept is to create a miniature city rising out of the vegetation of the garden, with insects and other creatures inhabiting the city as metaphorical and literal residents (Figure 62). By providing functional habitat structures and resources, viewers will get to see the organisms walk the streets, enter the buildings, and climb the stairs of the miniature city. Although these pieces are not serious design proposals for green architecture or urban planning, they are meant to evoke a future where humanity and nature are intertwined in the built environment. Because these sculptures create actual ecological activity in an actual populated area, they help in a small way to bring about the artistic vision they are modeled after.

Figure 62. Biophilic Cityscape. Source: RJH Artworks, 2021

I see the individual buildings in this installation as modules for experimenting with different habitat sculpture techniques. Although there are only a few buildings completed, the installation will need dozens of structures to evoke a diverse bustling metropolis of life rather than a few isolated apartment buildings that don’t combine into a larger whole. This provides ample room for testing different methods and techniques. In fact, it is possible for this cityscape installation to test every single habitat creation technique discussed so far this research (Figures 63 & 64). The sculpture shown above in Figure 62 was created at the beginning of this research project and does not incorporate many of the techniques and recommendations that I later learned about. For instance, the artificial nest cavities on its left side are made of glass, which is a material that is known to cause increased mortality in cavity-nesters from fungal and bacterial infection (MacIvor, 2017). I plan to modify this structure as shown below in Figure 63 to incorporate the new methods and techniques that I’ve developed.

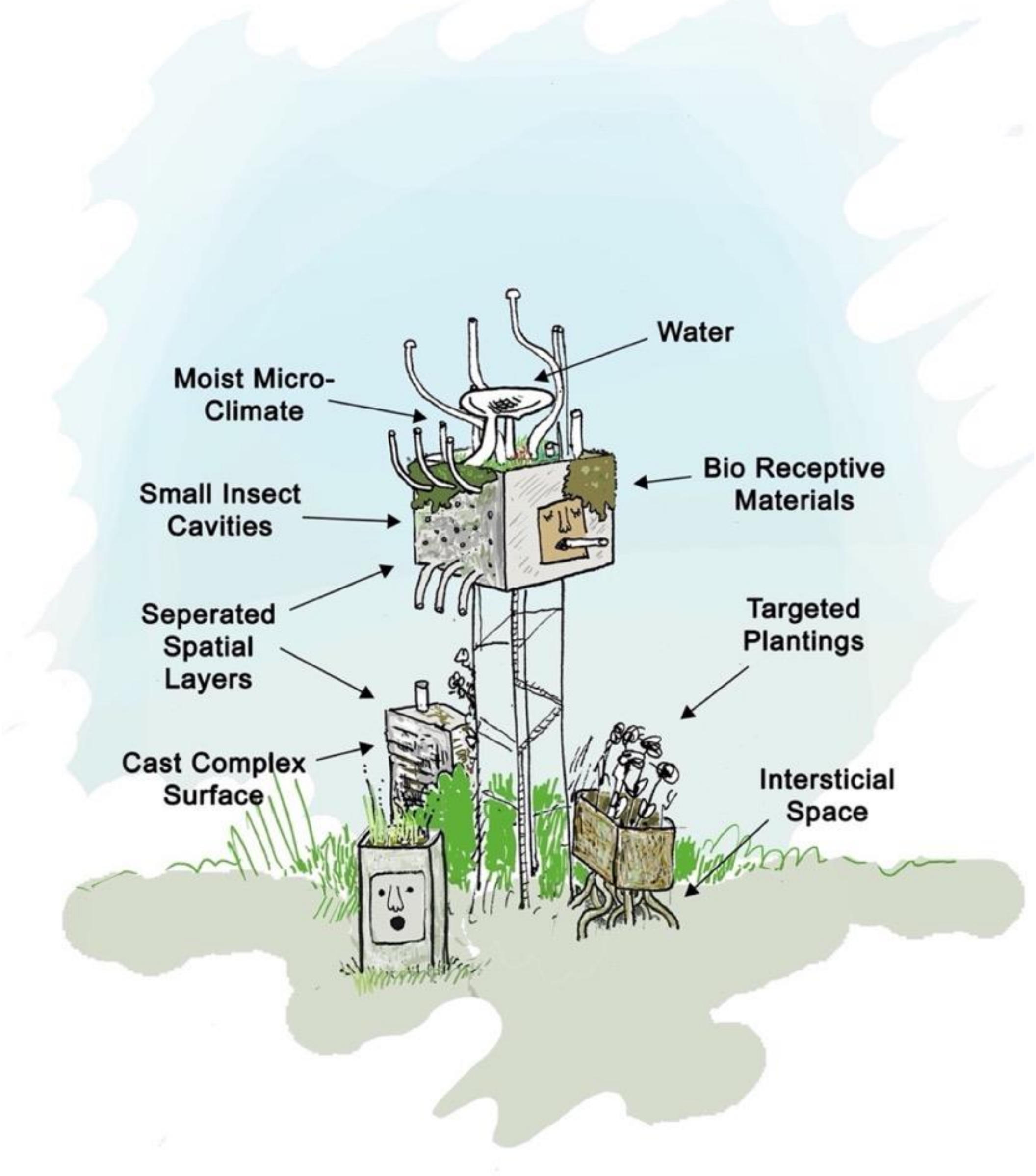


Figure 63. Diagram of habitat creating forms, properties, and resources. Source: RJH Artworks, 2022

The sculpture shown below (Figure 64) was developed later in the research process, and therefore incorporates many more of the techniques and recommendations from section 3. The use of a salvaged snag will likely increase the chances of sustaining ecological activity as opposed to the entirely artificial structure in Figure 62. The height of the snag also allows much more space for vertical stratification and niche segregation (section 3.1.3). The buildings in this piece were also specifically sized to hold cavities targeting native mammal and bird species, with room for ample insulation to improve thermal stability (Figure 65).

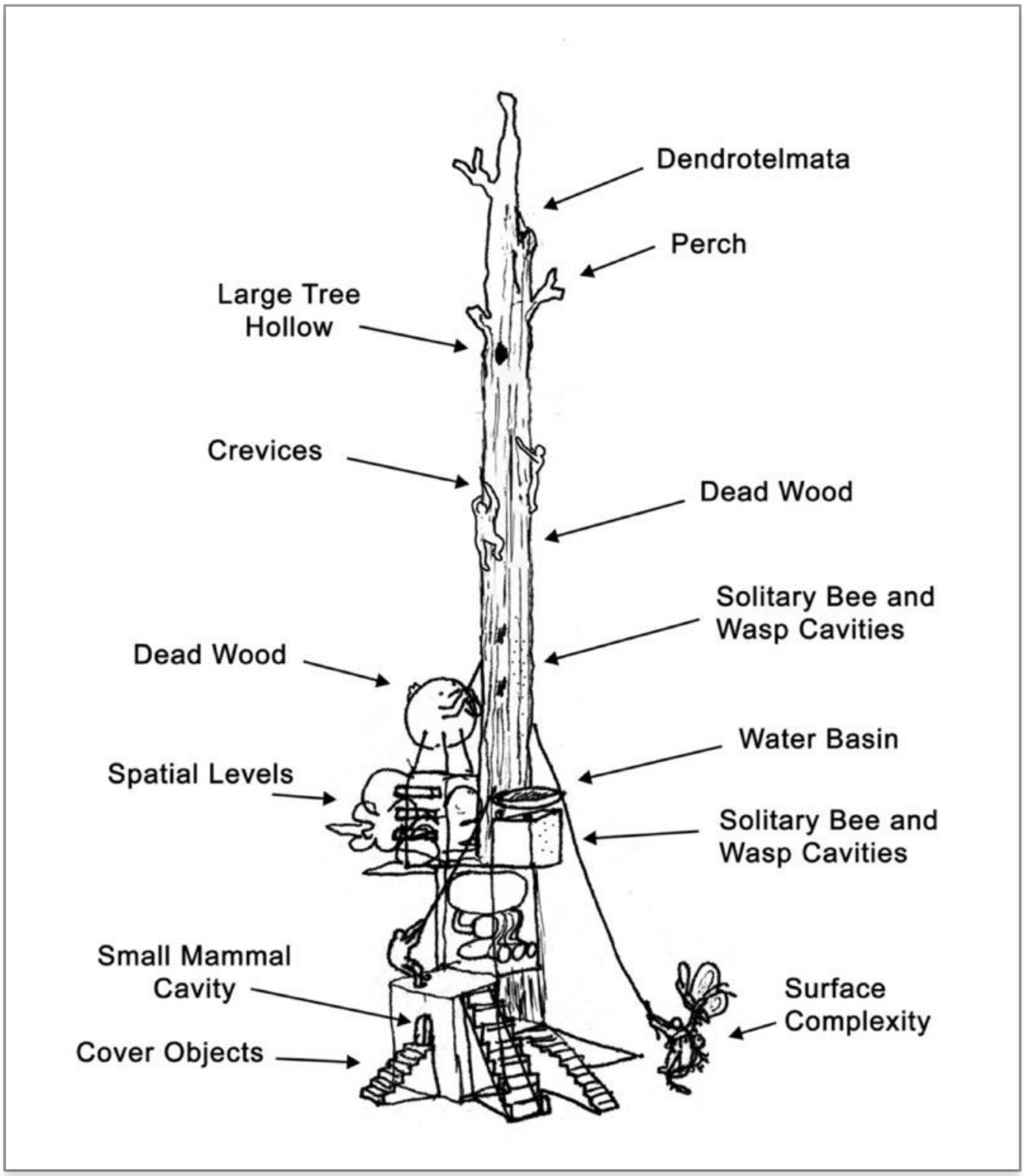


Figure 64. Diagram of habitat creating forms, properties, and resources. Source: RJH Artworks, 2022

Figure 65. Development of the main structure. (Left) modifies nest boxes will be inserted inside the building and encapsulated in woodcrete for thermal buffering, (center) the steel structure holding the building and the salvaged snag, (right) wooden mold for staircases. Staircases will function as cover objects where they meet the ground, and the space behind the staircases will be designed for use as interstitial space. Source: RJH Artworks, 2022

Figure 66. Figure made of decaying wood from a salvaged log. Materials added for moss colonization following methods from Chairunnisa & Susanto (2018) and Udawattha et al. (2018). Source: RJH Artworks, 2022

As this new piece of the *Biophilic Cityscape* installation is being fabricated, I am exploring exciting new methods of sculpting with highly decayed, or *veteris*, wood. In Figure 66 above, veteris wood was broken apart and grafted on to a steel frame to make one of the human forms in Figure 64. The wood was lashed into place with hemp twine soaked in a woodcrete mixture. This twine hardened into a durable exoskeleton that will hopefully be left behind when the wood and steel armature have disintegrated. Salvaged moss was planted onto the figure using a buttermilk mixture specified in Chairunnisa & Susanto (2018) and Udawattha *et al*. (2018). The sculpture overwintered outside my studio during winter 2021-2022, and signs of new growth are now visible in spring 2022 (Figure 66, right).

The next experimental method I am exploring involves encasing veteris wood in materials like concrete and woodcrete (Figure 67). My hope is that this casing will artificially create a moist dead wood microclimate where such microclimates may not be naturally available. In the sculpture shown below (the round figure holding a string from Figure 64), a highly decayed stump was salvaged and sculpted into a round form. This wood ball was placed on a steel armature and encased in modified woodcrete. The woodcrete mixture used sawdust and wood chips that came of the stump during the sculpting process, as well as salvaged wood mould. The mixture contained very little cement in the first layer, and progressively more cement as I worked outward to create a durable shell. A section of woodcrete is missing from the top of the sphere to let in rainwater and saproxylic organisms.

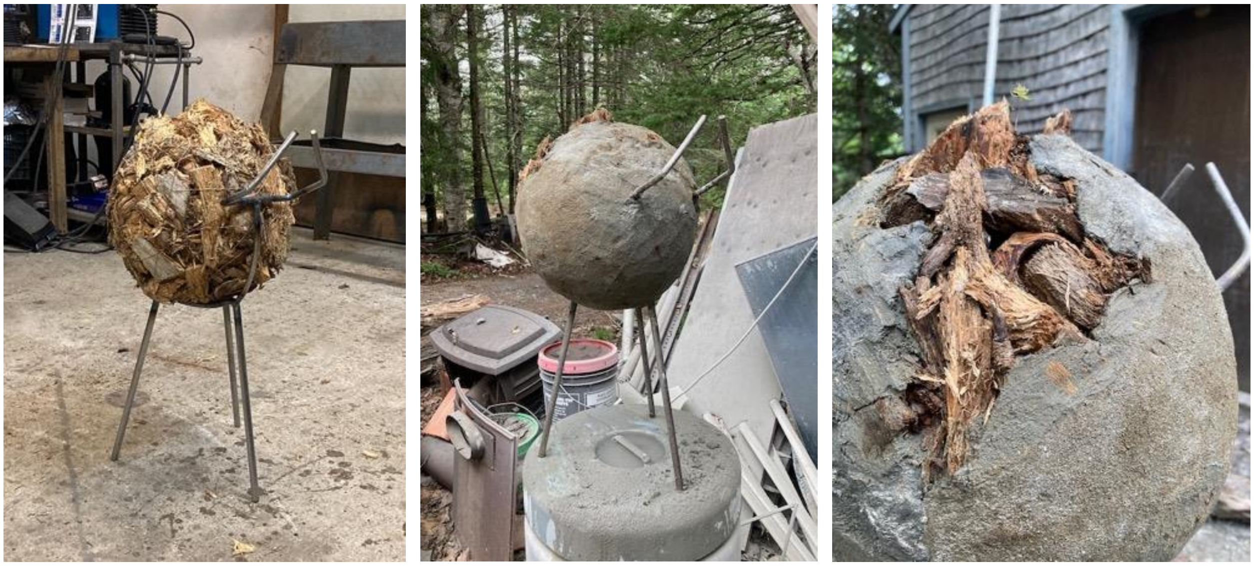


Figure 67. Salvaged stump encased in modified woodcrete. Source: RJH Artworks, 2022

Like all habitat sculpture installation, monitoring ecological activity after installation will be key to gauging the success of these experimental techniques. The various sculptures that make up the *Biophilic Cityscape* installation will be worked on over the summer of 2022 and will hopefully be exhibited at the Dorr Museum of Natural History in fall 2022.

4.2.3 Orbs (Artificial Habitat II)

Figure 68. Orbs (Artificial Habitat II). Source: RJH Artworks, 2022

This is a mixed-media sculpture made in 2020 using copper, ceramics, and glass. It was inspired by eastern chipmunks (*Tamias striatus*) outside my sculpture studio who would run through long drainage tubes that were left in a bundle on the ground (Figure 69). I noticed that the openings of the tubes had roughly the same diameter as the entryways to the chipmunk burrows that could be found nearby (1.9 cm).

Figure 69. An eastern chipmunk (Tamias striatus) would run back and forth through this tube multiple times a day

Figure 70. Game camera footage of experimental PVC tubes. (Left) American red squirrel (Tamiasciurus hudsonicus), (right) eastern chipmunk (Tamias striatus).

In the spring of 2020, I conducted an experiment and statistical analysis to see if chipmunks would preferentially use a certain size PVC tube when compared to red squirrels (*Tamiasciurus hudsonicus*) (Figure 70). The full experiment is included in Appendix A. Although small sample size means that reliable results could not be drawn, I found that chipmunks spend more time in tubes with a 2 cm internal diameter, while red squirrels spent more time in 3 cm tubes. When I creates *Spheres (Artificial Habitat II)* later in the summer of 2020, I used these measurements to determine copper pipe diameter for the base and entry hole diameter for the ceramic orbs (Figure 71). My hope was that chipmunks would run through the sculpture in the same way that they ran through the assortment of drainage tubes.

Although I found the experimental design and resulting data to be extremely useful for habitat sculpture, I had not yet researched all the other relevant components of habitat such as thermal properties and material attributes. I now believe the sculpture is unlikely to interact with small mammals in any ecologically significant way because of factors like the extreme thermal properties of exposed copper and the impermeability of glazed ceramic. However, the sculpture was installed at the DGC Permasculpture Garden in 2021, and I plan to monitor it closely to see if any unexpected ecological interactions or effects occur. There are also modifications that could be made to improve its qualities as habitat such as filling some of the orbs with wood mould, or burying the copper pipes so that they are thermally buffered. If modifications do not attract any organisms, or if I observe any harmful effects, I may seal the copper pipe entrances to minimize risk.

Figure 71. Orbs (Artificial Habitat II), detail. Source: RJH Artworks, 2022

4.2.4 Lichen Planter

This piece uses steel, plaster, glass, dead wood, and two clumps of salvaged *Cladonia* lichens (Figure 72, 73). The clumps of lichen are growing behind each plaster head and are connected by a hollow glass tube. I wanted insects and other inhabitants of the lichen to travel back and forth through the tube so you could see them making their daily commutes. Spongy dead wood was placed underneath the lichen clumps to retain moisture. After one month of being installed a spider set up in the middle of the tube to catch any passersby.

Figure 72. Lichen Planter, 2020. Source: RJH Artworks, 2020

Figure 73. Lichen Planter (detail), 2020. Source: RJH Artworks, 2020.

This piece was made early in the research process, and so doesn't contain many of the structures and techniques that I now know would increase its ecological value. I would like to make more pieces with a similar visual conceptual framework, but with modifications such as using bio-receptive materials and incorporating multiple spatial levels and salvaged habitat structures.

4.3 PLANNED SCULPTURE INSTALLATION IN PHILADELPHIA

Artificial habitat sculptures in heavily urbanized environments will have to be very different in terms of their ecological functionality and aesthetics compared with those in less developed suburban or rural settings. I am particularly excited about the possibilities of creating these pieces in cities because of the unique opportunities they present. I am planning an installation in Philadelphia because of my ties to the arts community in the city and my experience of living in neighborhoods with very little green space like Central South Philadelphia and Point Breeze.

Locke *et al*. (2020) showed that across 37 metropolitan areas in the US, neighborhoods inhabited by racial and ethnic minorities had on average 23% less canopy cover than they did 80 years ago, and neighborhoods characterized by large US born White populations had an average of 43% more canopy cover than 80 years ago. Decades of research has shown that systematic dis-investment in low-income neighborhoods and communities of color, and the preferential placement of parks and vegetation projects in affluent and predominantly white neighborhoods has caused this situation (Borunda, 2020, Locke *et al.,* 2020, Rowland-Shea, 2020). This situation has been revealed to be even more problematic than previously thought by a developing body of research showing the negative effects of *nature deprivation*[9] in marginalized communities on physical health, mental health, and many socio-economic life outcomes (Berman *et al*., 2012, Gregory *et* al., 2015, Rowland-Shea, 2020, South *et al*., 2015, South *et al*. 2018). The harm caused by the lack of green space in marginalized neighborhoods is also being exacerbated by the current global pandemic where natural outdoor spaces provide a much-needed reprieve from lockdown and the many stresses and traumas being endured (Borunda 2020).

After living in the city for a short while, I realized that habitat sculpture installations could be an effective method to combat this situation on many fronts. First and foremost, these installations would by definition provide exposure to nature and non-human organisms. Even if the contributions of the sculptures themselves didn't live up to their full potential, the plantings and landscaping that surround them would be providing green space. Additionally, these sculpture installations would open up a separate funding source than would be available for traditional parks, gardens, and greening projects. Much like Mel Chin's *Revival Field* accessed funding from the National Endowment for the Arts when Dr. Rufus Cheney could not get funding to study hyperaccumulating plants from science organizations, these sculpture installations could be funded by arts organizations in addition to or instead of traditional funding sources (Art21, 2004). This is especially true in Philadelphia, which has had a robust public arts funding infrastructure that dates back to the public arts programs of the New Deal era and the anti-graffiti Mural Arts Program of the 1980s (Philadelphia Department of Recreation, 2006, Mural Arts, 2006). Philadelphia has more murals per capita than any other city in the world, and there are current efforts being made to direct arts funding to low-income and minority neighborhoods in the city (City of Philadelphia, 2004, Hilario, 2016, McGovern, 2005).

The sculpture installation I am planning will be community based, with heavy involvement from local artists and neighborhood residents. The process of choosing a specific site in the city will be informed by the level of interest and desired involvement expressed by local communities. Even though I lived in the city for several years and have ties there, as a middle-class white person from Maine I risk coming into a community that I may not understand to impose a project that may not be wanted. Special attention will have to be paid to this issue so that the project truly benefits residents and reflects their wishes more than my

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[9] Neighborhoods are considered nature deprived if they contain more human disturbance of the landscape than the state average (Rowland-Shea 2020).

own. I have put together concept sketches for this installation (Figures 75, 76), but I am keeping the options open until a site has been selected and partnerships formed.

Figure 75. Proposal sketch for habitat sculpture installation in Philadelphia. A dead wood sculpture conveys sacredness through religious symbolism and materials. Source: RJH Artworks

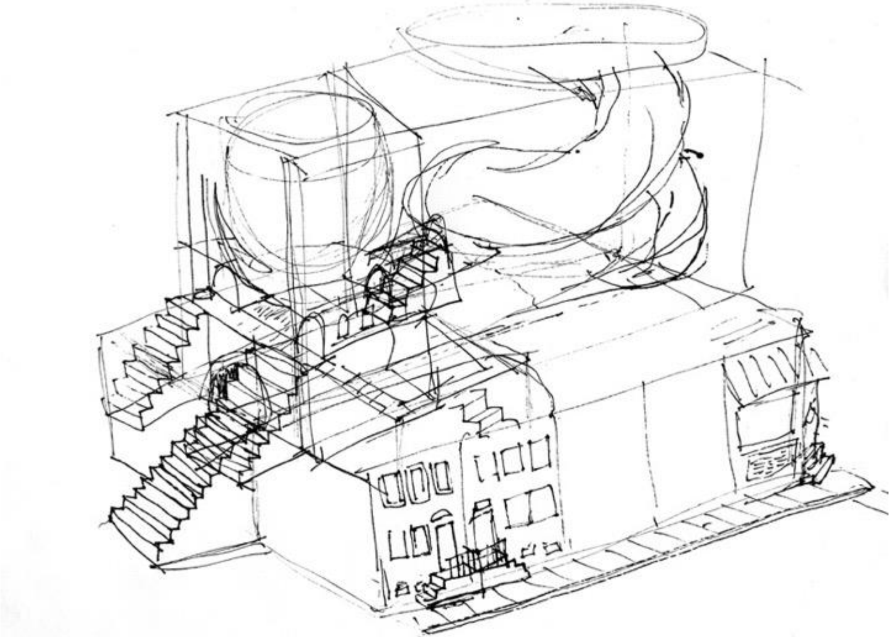

Figure 76. Proposal sketch for habitat sculpture installation in Philadelphia. A miniature cityscape in a garden reflects the city's aesthetics while providing habitat. Source: Robert Haskell, 2020

4.4 THE GNOME HOME

The gnome home is a sculptural earthbag structure that is being built on the property of Sweet Pea's Farm in Bar Harbor, Maine (Figure 77). It was started by a team that included Middlebury College student Luna Shen, builder Anthony Young, and myself. The project received funding through a competitive grant from Middlebury College in 2018, and construction was started later that year. The concept for the structure was that it would provide shelter to humans on the inside, and habitat to wild organisms on the outside. It was also inspired by Luna's experience with traditional Chinese homes such as 窑洞 (cave dwellings) and 土楼 (an earthen building that can be translated as "mud building").

The structure of the Gnome Home is built out of sandbags filled with clay-heavy soil mix and a small amount of cement. Once the main structure is built, it will be covered in soil from a nearby pile of dirt that was left after excavating a pond on the property. While this project has been in progress for several years, I hope to use the insights and novel approaches developed during this research to create sculptural habitat structures built into the outer envelope of the Gnome Home. These structures will include cavities, interstitial spaces, complex surface textures, and separated spatial levels (not shown below).

Figure 77. Digital illustration of the Gnome Home. Source: RJH Artworks, 2019.

Figure 78. Current state of construction as of spring, 2022.

5. CONCLUSION

Several novel methods and techniques for integrating habitat structures with sculptures have been developed in this research project. Monitoring and evaluation of these methods in the field could not be carried out in the timeframe of this project, but this provides a clear direction for future research. The *Saproxylic Food Web* installation at the Dorr Museum of Natural History and installations at the DGC Permasculpture Garden in Ellsworth show the habitat sculpture approach can be successfully implemented. The key insights, methods, and techniques developed in this research include:

- Using sculptures to protect valuable habitat structures while educating the public about their ecological importance
- Incorporating salvaged habitat structures rather than constructing them entirely artificially
- Making molds (or 3D scans) of habitat structures like tree hollows, cover objects, and perches for replication
- Making molds (or 3D scans) of natural surfaces and textures for replication
- Using dead, decaying wood as a sculpture material
- Using and developing bio-receptive materials such as woodcrete
- Using measurements of entrance holes and cavity dimensions to target species
- Creating a variety of conditions, including gradients in microclimate to target diverse multi-species assemblages.
- Providing additional resources in installations sites to support a greater range of organisms and life stages
- Making structures and installations as large as possible to provide maximum niche space
- Being aware of risks such as ecological traps, invasive species spread, and spread of vector-mosquito species, and using monitoring to guard against these outcomes

The techniques developed here can be used to pursue many divergent and exciting artistic directions. It is my hope that this research can be used by sculptors and ecological artists, and that the concepts can be further explored and developed over time. Many of the most important factors that affect the success of habitat sculpture installations operate on larger scales and were not discussed in this thesis. Community support, input, and other social factors are relevant to the success of installations and must be considered in the planning and design process. The promise of the habitat sculpture approach in disadvantaged urban areas is clear, and will be the primary focus of my work moving forward.

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APPENDIX A: PVC TUBE DIAMETER STUDY

PVC TUBE DIAMETER PREFERENCE IN TAMIAS STRIATUS AND TAMIASCIURUS HUDSONICUS
Introduction to Statistics and Research Design
Susan Letcher & Sean Todd
13 March 2020

Introduction

This study aims to investigate the following question: do *Tamias striatus* (eastern chipmunk) and *Tamiasciurus hudsonicus* (red squirrel) show different preferences for PVC tubes based on the diameter of the tube? I am particularly interested in the specific interaction effects between species (factor A) and tube size (factor B). Therefore, the following research hypothesis will be tested using a two-factor between-subjects ANOVA: H_1) the interaction between tube size and species will have a significant effect on time spent interacting with a tube. The null hypothesis is: H_0) there is no interaction between species and tube size. A simple effects analysis will then be carried out to examine the specific interaction effects among the factors. If there are significant results, a Tukey HSD post hoc test will be conducted to examine the nature of specific interactions. For example, is the mean of time spent interacting with a 0.75” diameter tube significantly greater for *T. striatus* than for *T. hudsonicus*?

Methods

Experimental design

To determine if *T. striatus* and *T. hudsonicus* show different preferences for PVC tubes based on diameter, PVC tubes with three distinct diameters were placed in plots on a property in Salisbury Cove, Maine. Motion activated game cameras were then used to record any interactions the target species had with the tubes. The game camera footage was reviewed for any interactions. When there was an interaction, the species, the tube size, and the length of time the animal was directly interacting with the tube (in seconds) was recorded onto a spreadsheet.

Preference was inferred using the amount of time the animal spent directly interacting with a tube. For the purposes of this report ‘directly interacting’ is defined as the animal being in direct physical contact with the tube (e.g., sitting on top of it or being inside of it), sniffing the tube, biting the tube, scratching the tube, or otherwise investigating it (e.g., sticking just its head inside the tube and pulling it out multiple times).

The diameters of the tubes were 0.50” (tube 1), 0.75” (tube 2), and 1.25” (tube 3). Each tube was a standard 10’ length. The wall thickness was .12” on tube 1, and .18” on tubes 2 and 3. The tubes were purchased at a retailer shortly before the experiment began. Tubes were placed along the ground, parallel with each other, spaced 1’ apart (see Figure 1). The tube sets were oriented in a manner so that each tube would be equally distant from other objects. The rationale for this is that a tube that abuts a cover object such as a bush or woodpile may be interacted with more due to its position. Therefore, keeping the same distance from objects should eliminate variability due to object distance. The order in which the tubes were placed was also rotated at each plot in case order affects interaction time.

Site Selection

The sites were located on the property of Sweet Pea's which is a 133-acre working farm. The property has portions that are heavily disturbed, but most of the acreage is relatively undisturbed forest (Donlan et al. 2019). The most common plant community on the property is mixed coniferous forest. This is dominated by mature *Picea rubens* (red spruce) and less frequently *Pinus strobus* (eastern white pine). Other common trees include *Abies balsamea* (balsam fir), *Thuja occidentalis* (eastern white cedar), and *Acer rubrum* (red maple) (Donlan et al. 2019).

Six sites were chosen initially, but experiments were only carried out in four because of time constraints. Sites were chosen according to three criteria:

Whether or not there were confirmed recent sightings of *T. striatus* and *T. hudsonicus* at the site. This was based on field observations made by the College of the Atlantic's wildlife ecology class from fall 2019 (Donlan et al. 2019).

The site has an intermediate level of disturbance, as determined by the same wildlife ecology class (Donlan et al. 2019). There is research to suggest that animals used to human disturbance are more likely to explore novel objects, so sites were chosen with similar distances from disturbed areas to control for this factor (Lyons et al. 2017; Tryjanowski et al. 2016) The third criterion was distance from other sites. Sites were chosen that were >60 meters away from each other to put them far outside the primary use ranges of both species (Guerra & Vickery 1998). Figure 2 shows a map of the sites.

Control plots were not used because the effect of the tubes on overall activity of *T. striatus* or *T. hudsonicus* is not relevant to the research question. To determine preferences between species and tubes, all that is needed is the relative activity of the two species according to tube size.

Data collection

Tubes and game cameras were installed at each site at 2100 hours, when the target species are not active. Camera footage was collected the next day at the same time. Each observation of a direct interaction with a tube (DV) was analyzed for the species (Factor A) and tube size (Factor B). This information was put into an Excel spreadsheet, along with time, date, and temperature in case that information turned out to be useful for further analysis.

Statistical analysis

I used R Studio to conduct my statistical analysis. The code was exported to .docx format and included below. To test the null hypothesis (there is no interaction between species and tube size) It was decided to use a two-factor between-subjects ANOVA. Analysis started by visually examining the data to see if it fit the assumptions of a normal distribution and homoscedasticity for a parametric test. Histograms (code) were created , as well as a box plot (code) to visually examine the data. It was concluded that the data probably did not fit the assumptions of the test. A Shapiro-Wilk test for normality supported the data not being normally distributed (P = 3.048e-06), and a Brown-Forsythe test that supported the variances in the data not being equal (P = 0.000787). Several transformations on the DV (time spent interacting) were examined, and the same two tests were conducted on each transformation to see if they allowed the data to meet the test assumptions (code). A Box-Cox transformation allowed the data to meet the assumptions of normality and homoscedasticity according to a Shapiro-Wilk test (P = 0.1043), and Brown-Forsythe test (P = 0.0871) respectively. After visually examining the transformed data (code), a two-factor between subjects ANOVA proceeded.

If the ANOVA shows a significant interaction effect, a simple effects analysis will be carried out to examine the specific interaction effects among the factors. If there are significant results, a Tukey HSD post hoc test will be conducted to examine the nature of specific interactions between species (factor A) and tube size (factor B). Factor A has two levels: a1 = *T. striatus*, a2 = *T. hudsonicus*. Factor B has three levels: b1 = 0.50” diameter tube, b2 = 0.75” diameter tube, b3 = 1.25” diameter tube. The simple interaction effects are as follows:

Tube size (B) will significantly affect time spent interacting for *T. striatus* (a1).

Tube size (B) will significantly affect time spent interacting for *T. hudsonicus* (a1).

Species (A) will significantly affect time spent interacting with the 0.50” diameter tube (b1).

Species (A) will significantly affect time spent interacting with the 0.75” diameter tube (b2).

Species (A) will significantly affect time spent interacting with the 1.25” diameter tube (b3).

Results

A two-factor between-subjects ANOVA showed that the interaction between species and tube size had a significant effect on time spent (Box-Cox transformed) (F_2,60 = 7.334, P = 0.0014) (Table 1). Because of the significance of the interaction, the main effects cannot be reported.

An analysis of simple effects (code) showed that there was no significant difference in time spent (Box-Cox transformed) by *T. striatus* ($\bar{x}$ ± sd = <0.0001 ± <0.0001) and *T. hudsonicus* (0.1 ± 0.2108) with 0.50” diameter tube (F_1,20 = 2.727, P =0.4758), but every other simple effect had significance. In the case of the 0.75” tube, *T. striatus* spent significantly more time interacting (Box-Cox transformed) (00.50605 ± 0.4257) than *T. hudsonicus* (0.2023 ± 0.3365) (F_1,20 = 4.643, P = 0.0126). With the 1.25-inch tube, *T. hudsonicus* spent significantly more time interacting (Box-Cox transformed) (0.6613 ± 0.3557) than *T. striatus* (0.2707 ± 0.4051) (F_1,20 = 5.652, P = 0.0068). The simple effects analysis also showed that tube size had a significant effect on time spent (Box-Cox transformed) for *T. striatus* (F_2,33 = 8.189, P = 0.00129), as well as for *T. hudsonicus* (F_2,27 = 9.432, P = 0.0007). A post hoc Tukey HSD test will be conducted to further investigate these effects.

A post hoc Tukey's HSD test (Table 2) showed fewer significant effects than the analysis of simple effects. It showed that *T. striatus* spent significantly more time interacting (Box-Cox transformed) with the 0.75” tube than with the 0.50” tube (P = 0.0011), but it did not spent significantly more time interacting (Box-Cox transformed) with the 0.75” tube than it did with the 1.25-inch tube (P = 0.2620). It also did not spend significantly more time interacting (Box-Cox transformed) with the 1.25-inch tube than it did with the 0.50” tube (P = 0.3341). The analysis showed that *T. hudsonicus* spent significantly more time (Box-Cox transformed) interacting with the 1.25-inch tube than with the 0.50” tube (P = 0.0036), and significantly more time (Box-Cox transformed) interacting with the 1.25-inch tube than with the 0.75” tube (P = 0.0289). It did not show a significantly greater amount of time spent (Box-Cox transformed) with the 0.75” tube than with the 0.50” tube (P = 0.9808). The analysis did not show that *T. striatus* spent significantly more time interacting (Box-Cox transformed) with the 0.75” tube than *T. hudsonicus* (P = 0.1209), unlike the simple effects analysis. Likewise, it did not show that

T. hudsonicus spent significantly more time interacting (Box-Cox transformed) with the 1.25-inch tube than *T. striatus* like the simple effects analysis had shown, but it did come close to significance (P = 0.0708). Figure 3 shows a bar chart demonstrating the significant relationships among factors.

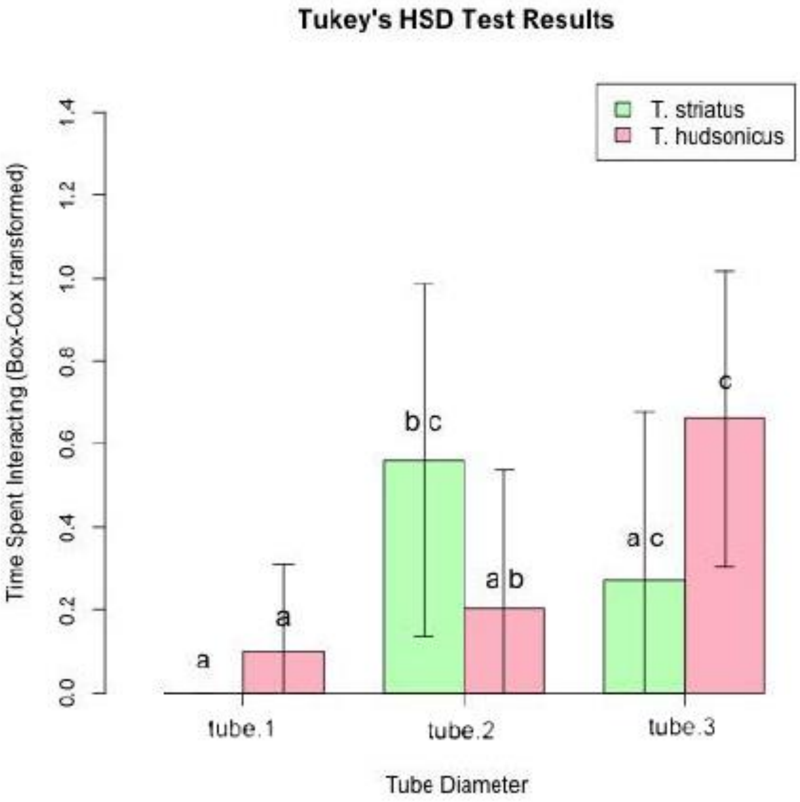

Figure 3. Tukey's HSD test results

Discussion

The analysis showed that *T. striatus* and *T. hudsonicus* do have different preferences for PVC tube diameter, but only in terms of the Box-Cox transformed DV. Some very interesting interactions between levels were revealed by the analysis of simple effects and the post hoc Tukey's HSD test. The most interesting of these interactions for my research are 1) *T. hudsonicus* shows a strong preference for the 1.25" tube over the other sizes; 2) *T. striatus* shows a preference for the 0.75" tube over the 0.50" tube. This would make sense based on the larger body size of *T. hudsonicus*. It might also lend support to the idea that interaction with the tube is driven by the animal's ability to fit inside the tube. However, there are several factors that make one reluctant to embrace the results, most of all due to small sample size.

The first issue is that the transformation applied to the DV was the most extreme of the transformations applied, and it still yielded only a slightly significant result in a Brown-Forsythe test of heteroscedasticity (P = 0.0871). It is suspected that the low variances in tube 1 due to small sample size may be disrupting the tests. Another issue is the disagreement between the analysis of simple effects and the post hoc Tukey's HSD test when it came to the effects of A at b2, and A at b3.

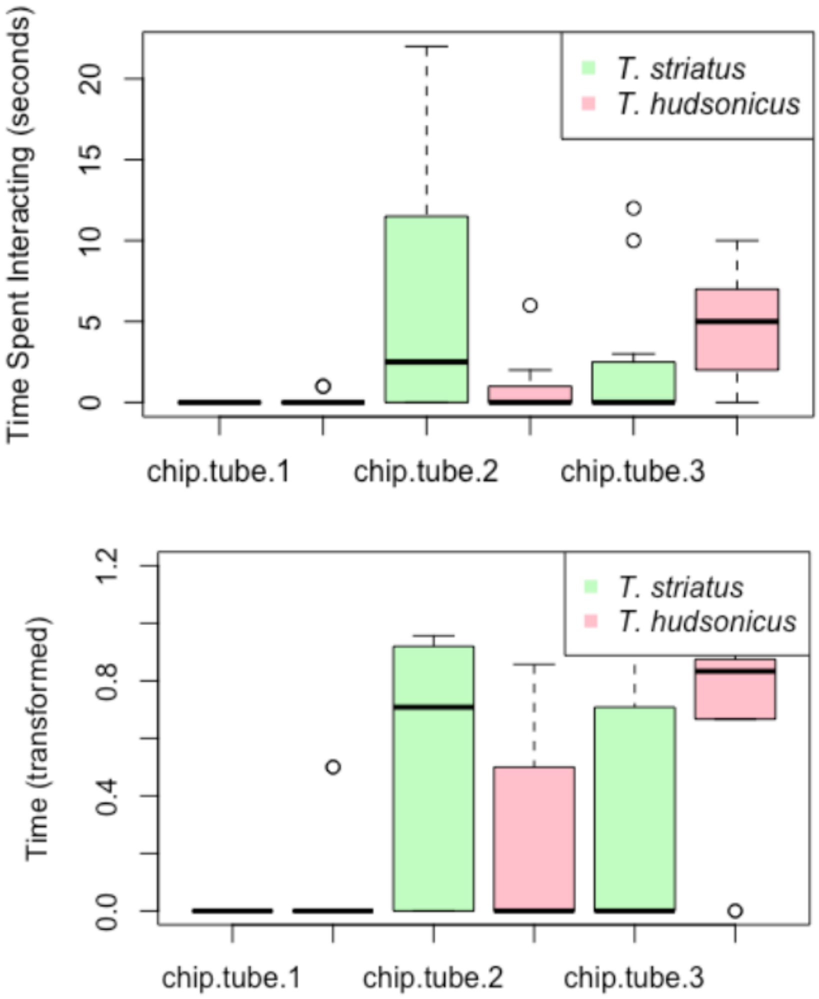

Figure 4. Comparison of raw data (left) versus Box-Cox transformed data (right)

If the sample size had been larger, perhaps the data would not have needed such a drastic transformation and some of these issues would be resolved. It also might be worth excluding tube 1 from further studies since it did not show much interaction with the animals.

With experiments like this, hopefully a body of research will be created that will aid in the creation of objects and physical spaces that successfully target specific species. Although the results do not offer a conclusive determination of the hypothesis, they do show promise in being able to differentially target specific species, even if those species share as many habitat requirements and characteristics as *T.s striatus* and *T. hudsonicus*. Some other independent variables that would be interesting to look at utilizing the same experimental design include tube length, material, placement in environment, and stability. It is hoped that by utilizing a combination of effects that are weak on their own, one could create objects that strongly select one species and exclude others.

Works Cited

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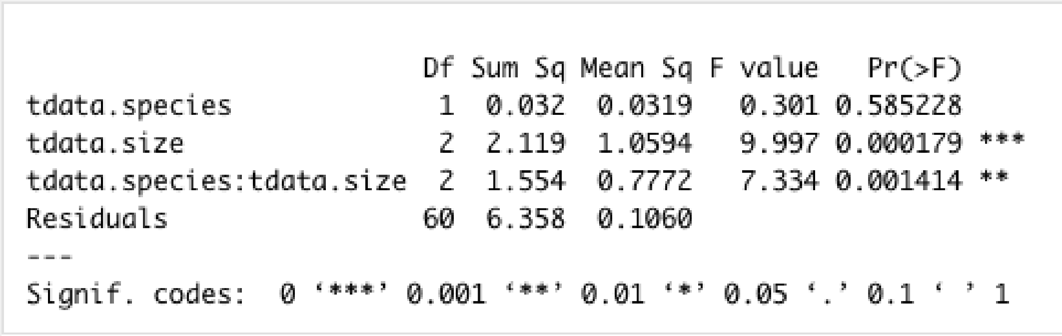
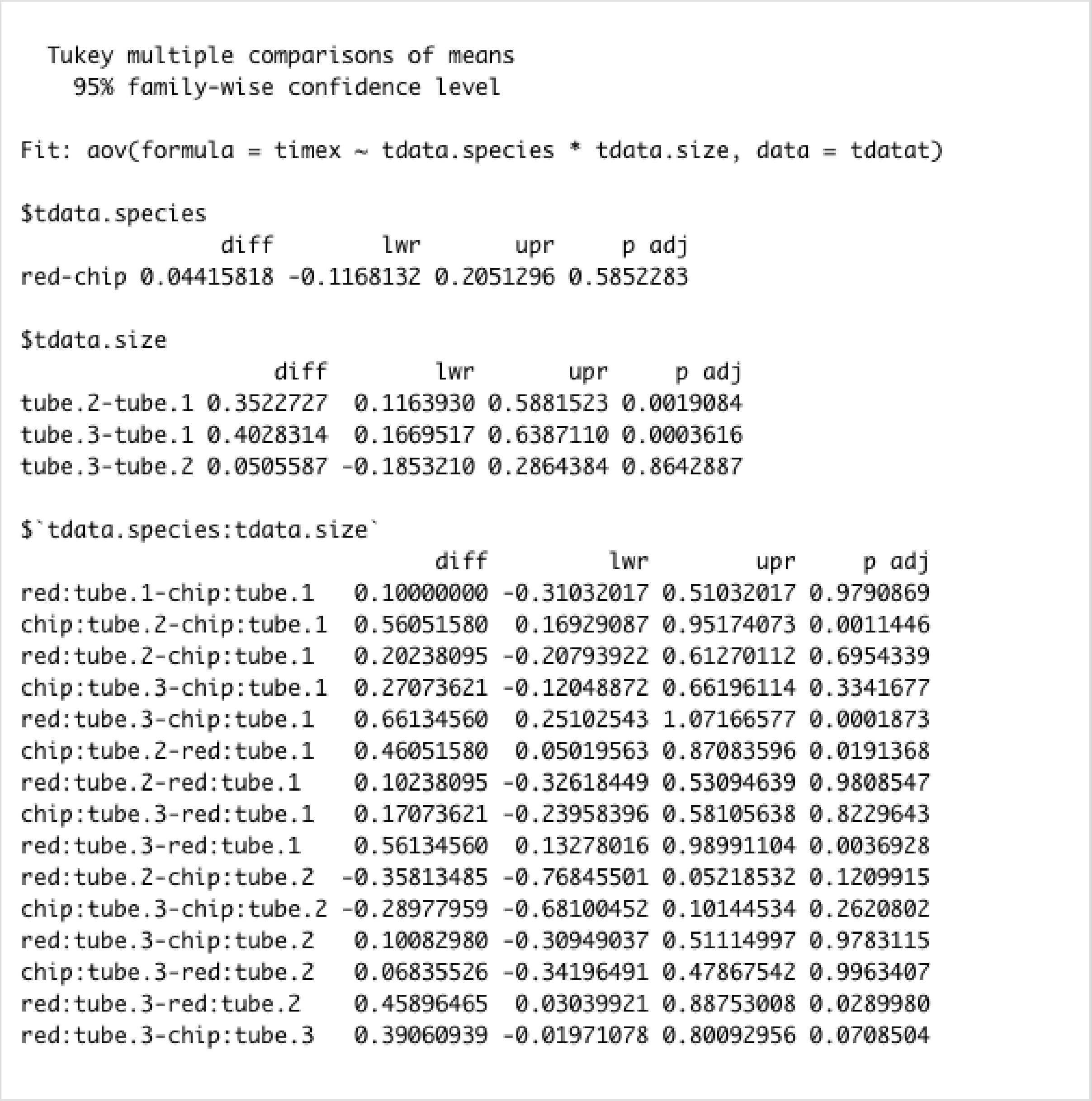
Table 1: Two-factor between-subjects ANOVA results



```
                          Df Sum Sq Mean Sq F value   Pr(>F)    
tdata.species              1  0.032  0.0319   0.301 0.585228    
tdata.size                 2  2.119  1.0594   9.997 0.000179 ***
tdata.species:tdata.size   2  1.554  0.7772   7.334 0.001414 ** 
Residuals                 60  6.358  0.1060                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 2: Tukey HSD Results



```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = timex ~ tdata.species * tdata.size, data = tdatat)

$tdata.species
               diff        lwr       upr     p adj
red-chip 0.04415818 -0.1168132 0.2051296 0.5852283

$tdata.size
                   diff        lwr       upr     p adj
tube.2-tube.1 0.3522727  0.1163930 0.5881523 0.0019084
tube.3-tube.1 0.4028314  0.1669517 0.6387110 0.0003616
tube.3-tube.2 0.0505587 -0.1853210 0.2864384 0.8642887

$`tdata.species:tdata.size`
                               diff         lwr        upr     p adj
red:tube.1-chip:tube.1   0.10000000 -0.31032017 0.51032017 0.9790869
chip:tube.2-chip:tube.1  0.56051580  0.16929087 0.95174073 0.0011446
red:tube.2-chip:tube.1   0.20238095 -0.20793922 0.61270112 0.6954339
chip:tube.3-chip:tube.1  0.27073621 -0.12048872 0.66196114 0.3341677
red:tube.3-chip:tube.1   0.66134560  0.25102543 1.07166577 0.0001873
chip:tube.2-red:tube.1   0.46051580  0.05019563 0.87083596 0.0191368
red:tube.2-red:tube.1    0.10238095 -0.32618449 0.53094639 0.9808547
chip:tube.3-red:tube.1   0.17073621 -0.23958396 0.58105638 0.8229643
red:tube.3-red:tube.1    0.56134560  0.13278016 0.98991104 0.0036928
red:tube.2-chip:tube.2  -0.35813485 -0.76845501 0.05218532 0.1209915
chip:tube.3-chip:tube.2 -0.28977959 -0.68100452 0.10144534 0.2620802
red:tube.3-chip:tube.2   0.10082980 -0.30949037 0.51114997 0.9783115
chip:tube.3-red:tube.2   0.06835526 -0.34196491 0.47867542 0.9963407
red:tube.3-red:tube.2    0.45896465  0.03039921 0.88753008 0.0289980
red:tube.3-chip:tube.3   0.39060939 -0.01971078 0.80092956 0.0708504
```

Supplemental Figures

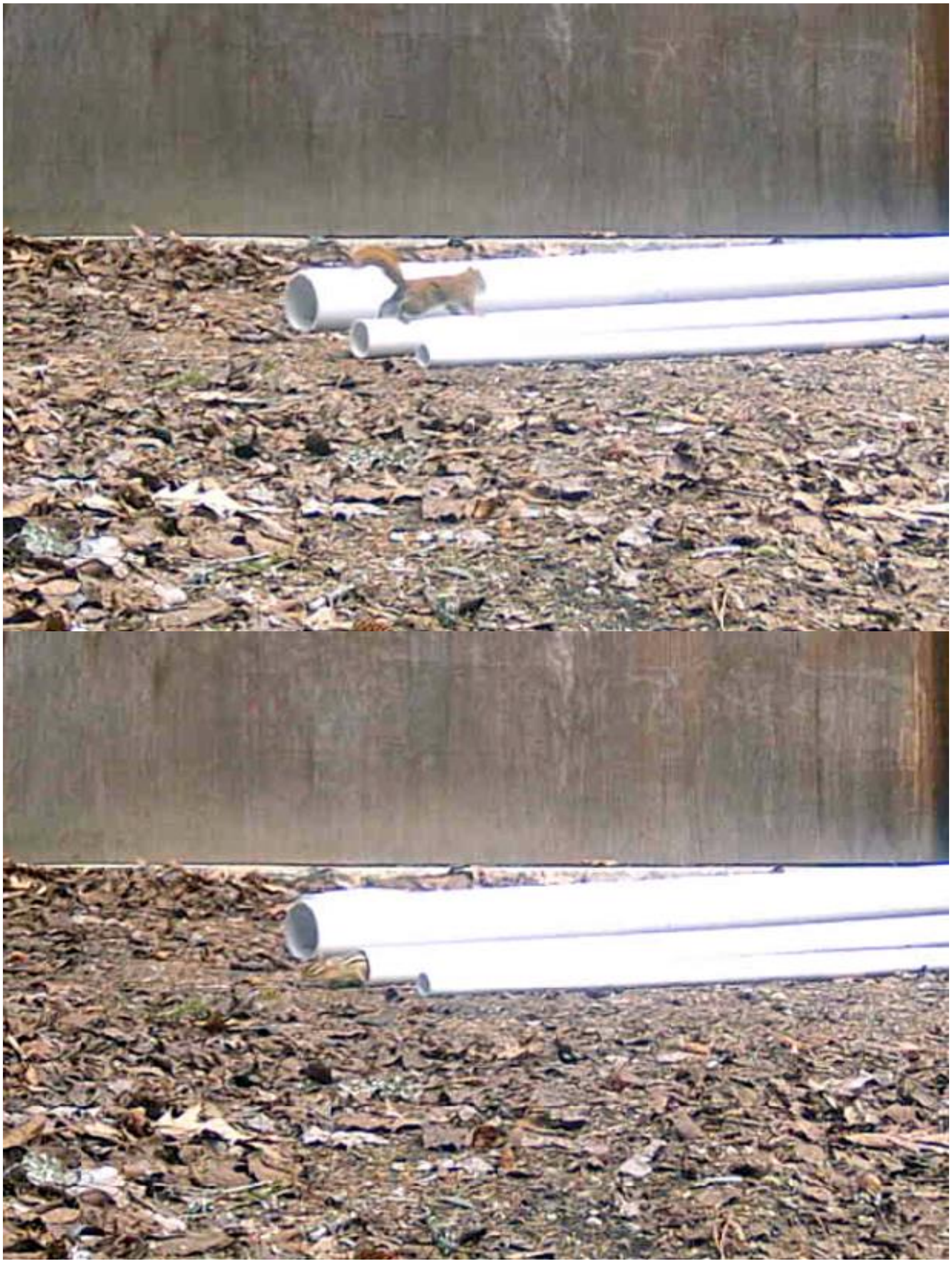


Figure 1: Side view of tubes. *T. hudsonicus* (top) and *T. striatus* (bottom) interacting with tubes

R Code (Exported to .docx)

PVC Tube Diameter Preference in *Tamias striatus* and *Tamiasciurus hudsonicus*

Robert Haskell

3/15/2020

Introduction

In this dataset, game cameras observed how long (in seconds) T. striatus and T. hudsonicus interacted with a 0.50-inch diameter PVC tube, a 0.75-inch diameter PVC tube, and a 1.25-inch diameter PVC tube. I will use a two-factor between-subjects ANOVA to analyze my results. I am primarily interested in any possible interaction effects, so I will conduct a simple effects analysis, and then use a Tukey HSD post hoc test to determine which specific interactions are significant.

Loading Raw Data and Running Packages

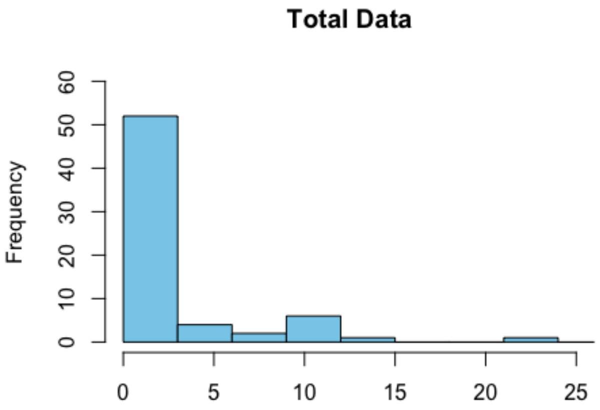
```
# Original dataset
tdata=read.csv(paste0(base_dir,"data15.csv"),header=T)
# Modified dataset for interaction plots
tdata2=read.csv(paste0(base_dir,"data16.csv"),header=T)
# Making integer vectors in tdata2 numeric
tdata2$time=as.numeric(tdata2$time)
# Making character vectors in tdata2 factors
tdata2$size=as.factor(tdata2$size)
# Modified vector for transformations
tdata3=tdata$time+1
# Other objects and packages
mycols=c("darkseagreen1","pink")
legendtext=c("T. striatus"[1],"T. hudsonicus"[1])
library(psych)
library(car)
```

Analyzing Data for Normality and Homoscedasticity

```
str(tdata)
## 'data.frame':    66 obs. of  3 variables:
##  $ species: chr  "chip" "chip" "chip" "chip" ...
##  $ time   : int  0 3 0 0 2 0 0 2 0 0 ...
##  $ size   : chr  "tube.1" "tube.2" "tube.3" "tube.1" ...
```

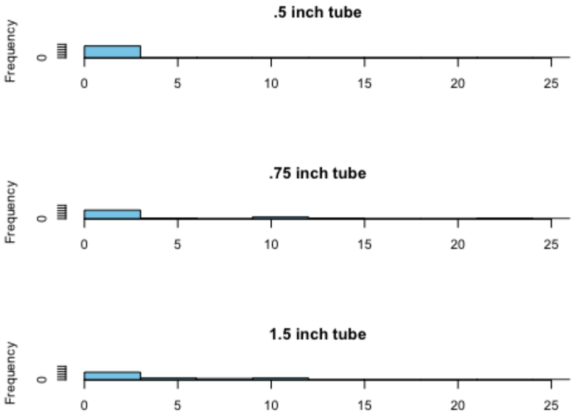
Using histograms to visually analyze data

```
# Histogram of total data
breakpoints=seq(0,30,by=3)
hist(tdata$time,main="Total
Data",xlab="",xlim=c(0,25),ylim=c(0,60),col="skyblue",breaks = breakpoints)
```

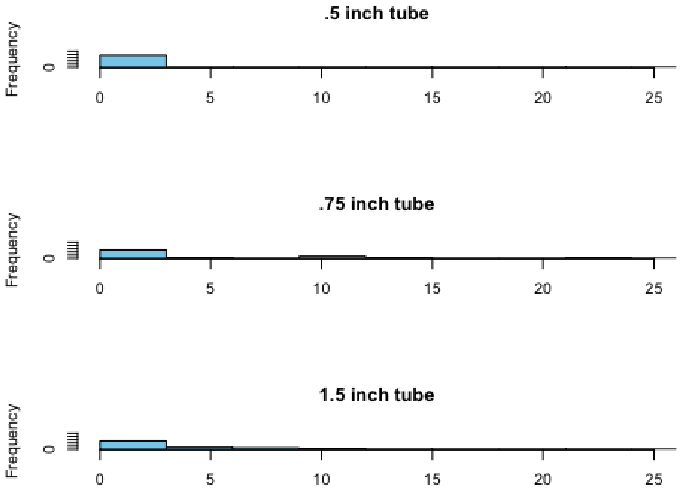


```
# Histograms of data by tube size
par(mfrow=c(3,1))
hist(tdata$time[tdata$size=="tube.1"],main="0.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
hist(tdata$time[tdata$size=="tube.2"],main="0.75 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
```

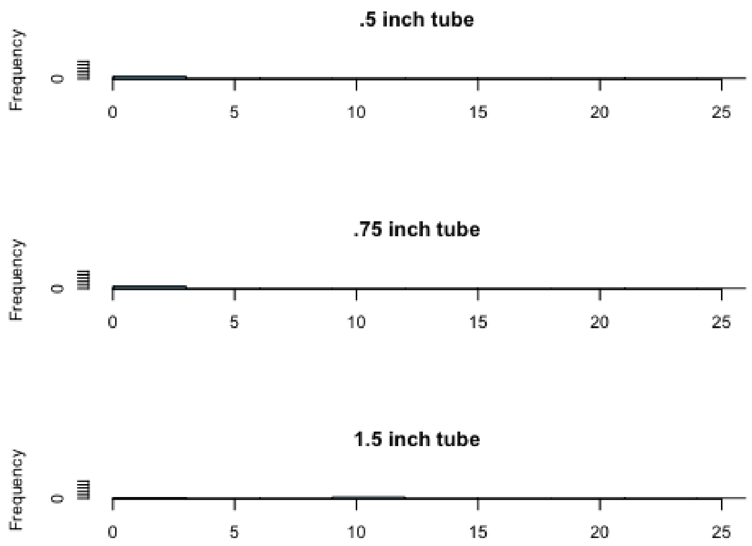
```
hist(tdata$time[tdata$size=="tube.3"],main="10.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
```



```
# Histograms of data by tube size and species
# Tamias striatus
par(mfrow=c(3,1))
hist(tdata$time[tdata$size=="tube.1"][tdata$species=="chip"],main="0.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
hist(tdata$time[tdata$size=="tube.2"][tdata$species=="chip"],main="0.75 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
hist(tdata$time[tdata$size=="tube.3"][tdata$species=="chip"],main="10.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
```

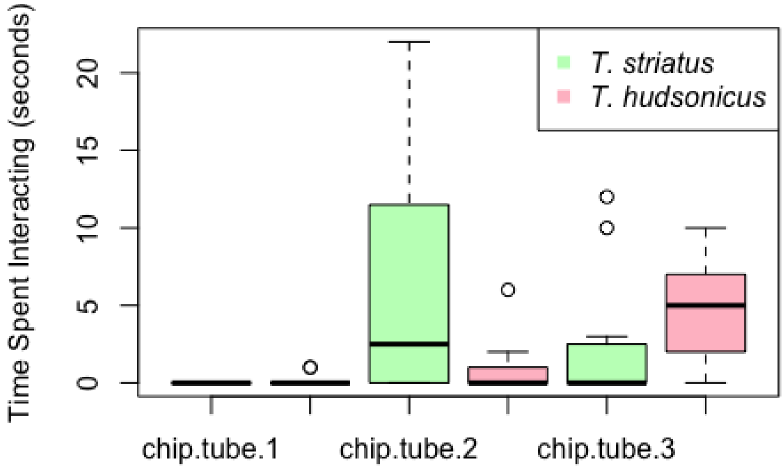


```
# Tamiasciurus hudsonicus
par(mfrow=c(3,1))
hist(tdata$time[tdata$size=="tube.1"][tdata$species=="red"],main="0.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
hist(tdata$time[tdata$size=="tube.2"][tdata$species=="red"],main="0.75 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
hist(tdata$time[tdata$size=="tube.3"][tdata$species=="red"],main="10.50 inch
tube",xlab="",xlim=c(0,25),ylim=c(0,25),col="skyblue",breaks = breakpoints)
```



Using a box plot to visually analyze data

```
plot1=boxplot(tdata$time~tdata$species*tdata$size,xlab="",ylab="Time Spent
Interacting (seconds)",ylim=c(0,22),col=mycols)
legend("topright",legend = legendtext,col=mycols,pch=15,text.font = 3)
```



Conclusion of visual analysis

The data look like they do not meet the assumptions of a normal distribution or homogeneity of variance, but to make sure I will conduct two tests: a Shapiro-Wilk test for normality, and a Brown–Forsythe test for homoscedasticity.

Conducting a Shapiro-Wilk test for normality

A significant result means that the data are not normally distrubuted.

```
model1=lm(time~species*size,data=tdata)
x=residuals(model1)
shapiro.test(x)
##
##  Shapiro-Wilk normality test
##
## data:  x
## W = 0.86267, p-value = 3.048e-06
```

Result: The data are not normally distributed (p=3.048e-06).

Conducting a Brown–Forsythe test for homogeneity of variances

A significant result means that the variances in the data violate the assumption of homogeniety (the Brown–Forsythe test is not sensitive to non-normality in data).

```
leveneTest(x~species*size,data=tdata)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value   Pr(>F)
## group  5  4.9076 0.000787 ***
##       60
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

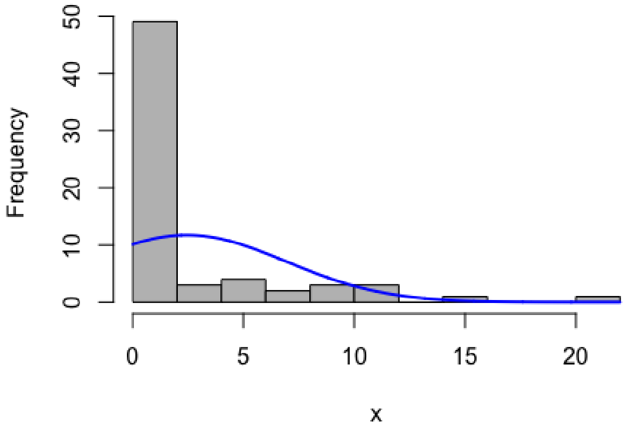
Result: The variances in the data violate the assumption of homogeniety (p=0.000787).

Conclusion: The data violate both the assumptions of normality and homoscedasticity

I will apply a transformation to try and make the data normal and homoscedastic.

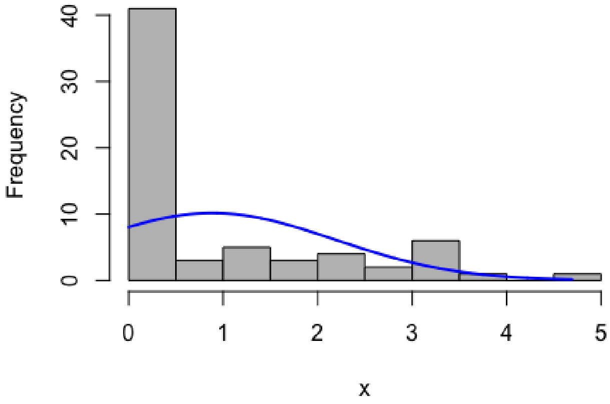
Examining different transformations, and testing them for normality and homoscedasticity

```
# No transformation for reference
plotNormalHistogram(tdata$time)
```



Square root transfromation

```
data_sqrt=sqrt(tdata$time)
plotNormalHistogram(data_sqrt)
```



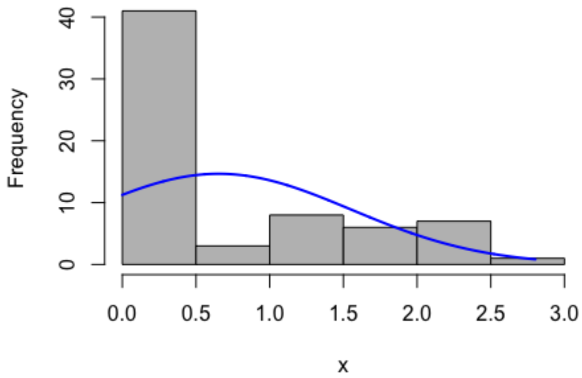
```
# Shapiro-Wilk test
model2=lm(data_sqrt~tdata$species*tdata$size)
x2=residuals(model2)
shapiro.test(x2)
##
##  Shapiro-Wilk normality test
##
```

```
## data:  x2
## W = 0.93932, p-value = 0.002954
# Brown–Forsythe test
leveneTest(x2~tdata$species*tdata$size)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value   Pr(>F)   
## group  5  4.4311 0.001682 **
##       60                    
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Results: The transformation does not make the data normally distributed (p=0.002954) or homoscedastic (p=0.001682).

Cube root transformation

```
data_cub=sign(tdata$time)*abs(tdata$time)^(1/3)
plotNormalHistogram(data_cub)
```

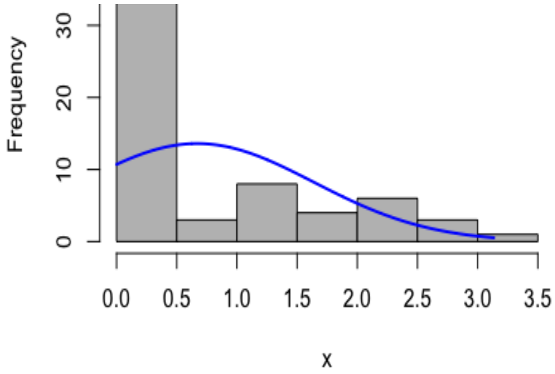


```
# Shapiro-Wilk test
model3=lm(data_cub~tdata$species*tdata$size)
x3=residuals(model3)
shapiro.test(x3)
## 
##  Shapiro-Wilk normality test
## 
## data:  x3
## W = 0.95635, p-value = 0.02074
# Brown–Forsythe test
leveneTest(x3~tdata$species*tdata$size)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value  Pr(>F)  
## group  5  3.1884 0.01283 *
##       60                  
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Results: The transformation does not make the data normally distributed (p=0.02074) or homoscedastic (p=0.01283).

Log transformation

```
data_log=log(tdata$time+1)
plotNormalHistogram(data_log)
```

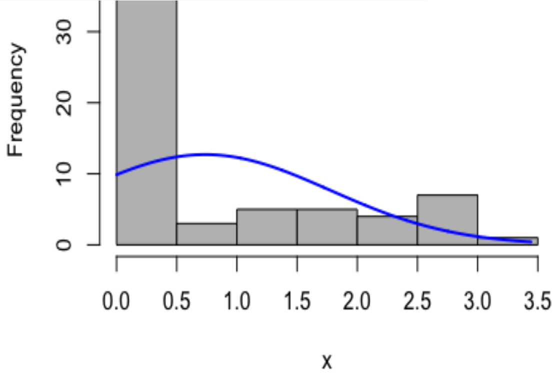


```
# Shapiro-Wilk test
model4=lm(data_log~tdata$species*tdata$size)
x4=residuals(model4)
shapiro.test(x4)
##
##  Shapiro-Wilk normality test
##
## data:  x4
## W = 0.94571, p-value = 0.006013
# Brown-Forsythe test
leveneTest(x4~tdata$species*tdata$size)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value   Pr(>F)
## group  5  4.2715 0.002175 **
##       60
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Results: The transformation does not make the data normally distributed (p=0.006013) or homoscedastic (p=0.002175).

Tukey's ladder of powers transformation

```
data_tuk=transformTukey(tdata$time,plotit=FALSE)
##
##     lambda      W Shapiro.p.value
## 417    0.4 0.7215       7.021e-10
##
## if (lambda >  0){TRANS = x ^ lambda}
## if (lambda == 0){TRANS = log(x)}
## if (lambda <  0){TRANS = -1 * x ^ lambda}
plotNormalHistogram(data_tuk)
```

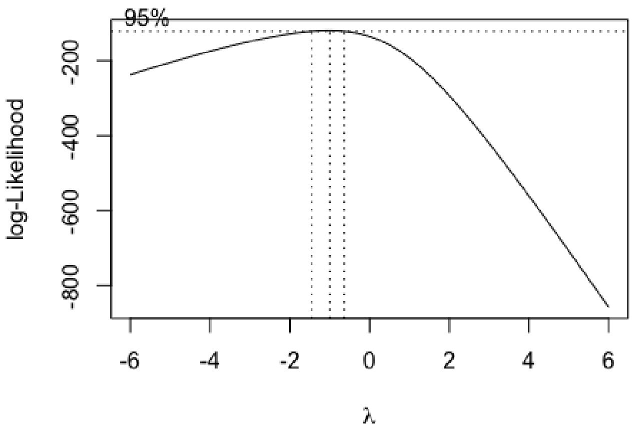


```
# Shapiro-Wilk test
model5=lm(data_tuk~tdata$species*tdata$size)
x5=residuals(model5)
shapiro.test(x5)
##
##  Shapiro-Wilk normality test
##
## data:  x5
## W = 0.94862, p-value = 0.008377
# Brown–Forsythe test
leveneTest(x5~tdata$species*tdata$size)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value   Pr(>F)
## group  5  3.7343 0.005214 **
##       60
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

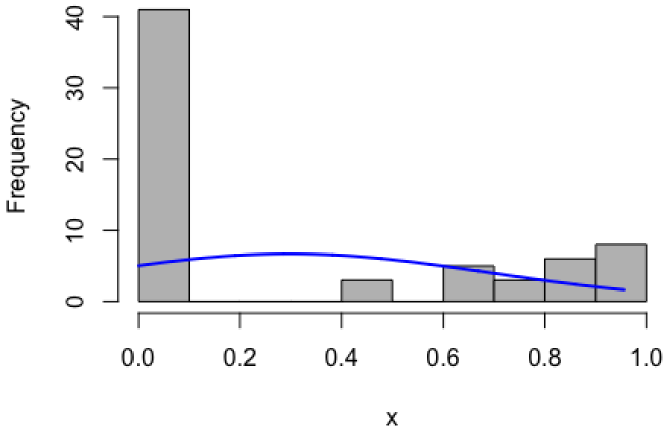
Results: The transformation does not make the data normally distributed (p=0.008377) or homoscedastic (p=0.005214).

Box-Cox transformation

```
box=boxcox(tdata3~1,lambda=seq(-6,6,0.1))
```



```
cox=data.frame(box$x,box$y)
cox2=cox[with(cox,order(-cox$box.y)),]
cox2[1,]
##    box.x    box.y
## 51    -1 -120.394
lambda=cox2[1,"box.x"]
timex=(tdata3^lambda-1)/lambda
plotNormalHistogram(timex)
```



```
# Shapiro-Wilk test
model6=lm(timex~tdata$species*tdata$size)
x6=residuals(model6)
shapiro.test(x6)
##
##  Shapiro-Wilk normality test
##
## data:  x6
## W = 0.96956, p-value = 0.1043
# Brown-Forsythe test
leveneTest(x6~tdata$species*tdata$size)
## Levene's Test for Homogeneity of Variance (center = median)
##       Df F value  Pr(>F)
## group  5  2.0303 0.08713 .
##       60
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Results: The transformation makes the data normally distributed (p=0.1043) and homoscedastic (p=0.08713).

Conclusion of transformation tests

The Box-Cox transformation is the only transformation that resulted in normality and homoscedasticity according to the Shapiro-Wilk test and Brown-Forsythe test. When visually examining the data, the cube root transformation looked to be the most normally distributed, but the tests say otherwise, so I will go with those results and use the Box-Cox transformation for my analysis.

Creating a new data frame with the transfromed data

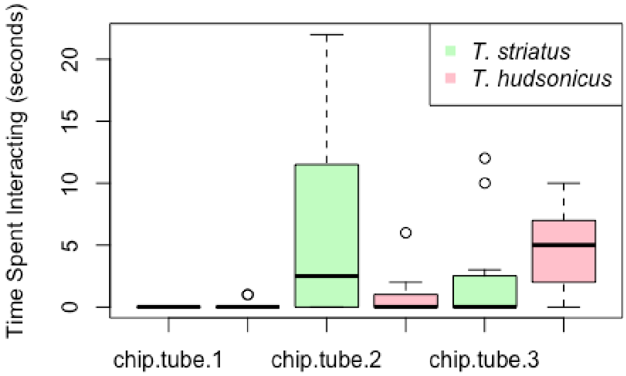
```
structure(timex)
##  [1] 0.0000000 00.7500000 0.0000000 0.0000000 0.6666667 0.0000000 0.0000000
##  [8] 0.6666667 0.0000000 0.0000000 0.0000000 0.8333333 0.0000000 0.0000000
## [15] 0.6666667 0.0000000 0.9090909 0.0000000 0.0000000 0.0000000 0.0000000
## [22] 0.0000000 0.0000000 00.7500000 0.0000000 0.0000000 0.6666667 00.50000000
## [29] 0.0000000 0.0000000 0.0000000 0.0000000 0.9230769 0.0000000 0.0000000
## [36] 0.9090909 0.0000000 0.0000000 0.8333333 0.0000000 0.0000000 00.7500000
## [43] 0.0000000 0.9375000 0.0000000 0.0000000 0.8571429 0.0000000 0.0000000
## [50] 0.9565217 0.9090909 0.0000000 0.9166667 0.0000000 0.0000000 0.0000000
## [57] 0.8750000 00.50000000 00.50000000 0.8571429 0.0000000 0.6666667 0.8888889
## [64] 0.0000000 0.9230769 0.0000000
tdatat=data.frame(tdata$species,timex,tdata$size)
str(tdatat)
## 'data.frame':    66 obs. of  3 variables:
##  $ tdata.species: chr  "chip" "chip" "chip" "chip" ...
```

```
##  $ timex        : num  0 00.75 0 0 0.667 ...
##  $ tdata.size   : chr  "tube.1" "tube.2" "tube.3" "tube.1" ...
```

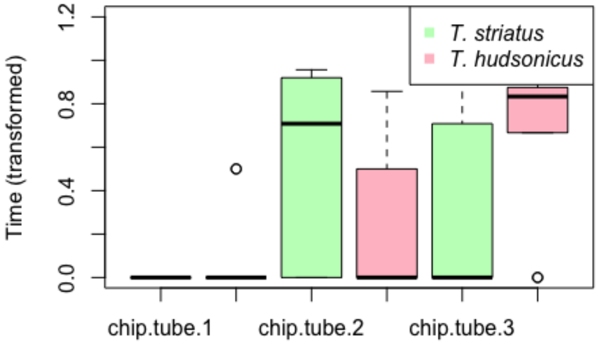
Examing Untransformed Data vs Transformed Data

Box Plots

```
# Untransformed box plot
plot1=boxplot(tdata$time~tdata$species*tdata$size,xlab="",ylab="Time Spent
Interacting (seconds)",ylim=c(0,22),col=mycols)
legend("topright",legend = legendtext,col=mycols,pch=15,text.font = 3)
```

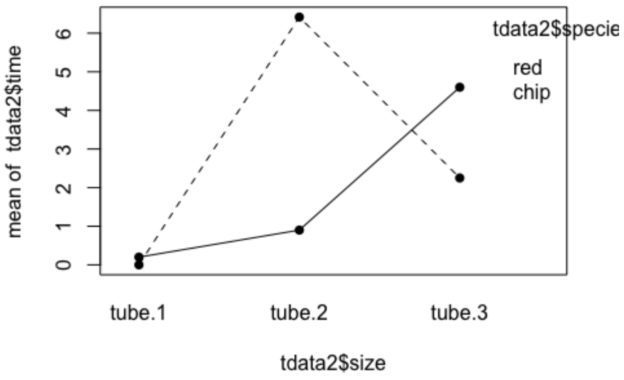


```
# Ttransformed box plot
plot2=boxplot(tdatat$timex~tdatat$tdata.species*tdatat$tdata.size,xlab="",ylab="Time
(transformed)",ylim=c(0,1.2),col=mycols)
legend("topright",legend = legendtext,col=mycols,pch=15,text.font = 3)
```

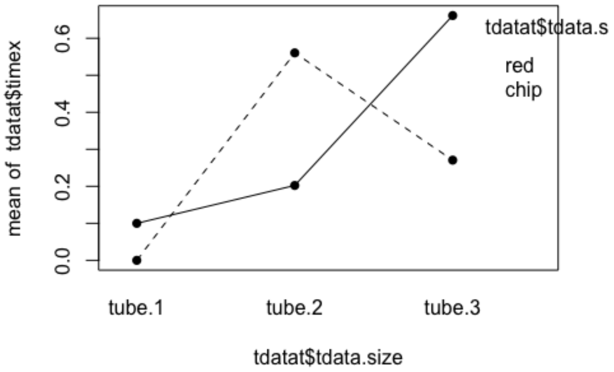


Interaction Plots

```
# Untransformed interaction plot
interaction.plot(x.factor=tdata2$size,trace.factor = tdata2$species,response=
tdata2$time, type="o",pch=16)
```



```
# Transformed interaction plot
interaction.plot(x.factor=tdatat$tdata.size,trace.factor =
tdatat$tdata.species,response= tdatat$timex, type="o",pch=16)
```



Conclusion

In the raw data, the difference in time spent between *T. striatus* and *T. hudsonicus* was the largest at tube 2, and the difference at tube 3 was smaller. In the transformed data that was flipped, with the difference in time spent between *T. striatus* and *T. hudsonicus* being the largest at tube 3, and smaller at tube 2.

Two-Factor Between-Subjects ANOVA on Transformed Data

```
aov2=aov(timex~tdata.species*tdata.size,data=tdatat)
aov2results=summary(aov2)
aov2results
##                          Df Sum Sq Mean Sq F value   Pr(>F)
## tdata.species             1  0.032  0.0319   0.301 00.5085228
## tdata.size                2  2.119  1.0594   9.997 0.000179 ***
## tdata.species:tdata.size  2  10.5054  0.7772   7.334 0.001414 **
## Residuals                60  6.358  0.1060
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Simple Effects Analysis on Transformed Data

Levels in dataset

A: species a1 = Tamias striatus a2 = Tamiasciurus hudsonicus

B: tube size b1: 0.50 inch b2: 0.75 inch b3: 1.25 inch

One-way ANOVAs to determine relevant sum of squares

```
# Creating subsets
chipm=subset(tdatat,tdata.species=="chip")
reds=subset(tdatat,tdata.species=="red")
```

```
small=subset(tdatat,tdata.size=="tube.1")
medium=subset(tdatat,tdata.size=="tube.2")
large=subset(tdatat,tdata.size=="tube.3")
MS_err=aov2results[[1]]$`Mean Sq`[4]
df_err=aov2results[[1]]$`Df`[4]
a = 2
b = 3
# Effect of species at the 0.50 inch tube
aov.Aatb1=aov(timex~tdata.species,data=small)
aov.Aatb1.results=summary(aov.Aatb1)
F.Aatb1=(aov.Aatb1.results[[1]]$`Mean Sq`[1])/MS_err
P.Aatb1=1-pf(F.Aatb1,df1=(a-1),df2=df_err)
P.Aatb1
## [1] 0.4758869
# Effect of species at the 0.75 inch tube
aov.Aatb2=aov(timex~tdata.species,data=medium)
aov.Aatb2.results=summary(aov.Aatb2)
F.Aatb2=(aov.Aatb2.results[[1]]$`Mean Sq`[1])/MS_err
P.Aatb2=1-pf(F.Aatb2,df1=(a-1),df2=df_err)
P.Aatb2
## [1] 0.01269071
# Effect of species at the 1.25 inch tube
aov.Aatb3=aov(timex~tdata.species,data=large)
aov.Aatb3.results=summary(aov.Aatb3)
F.Aatb3=(aov.Aatb3.results[[1]]$`Mean Sq`[1])/MS_err
P.Aatb3=1-pf(F.Aatb3,df1=(a-1),df2=df_err)
P.Aatb3
## [1] 0.00682045
# Effect of tube size on T. striatus
aov.Bata1=aov(timex~tdata.size,data=chipm)
aov.Bata1.results=summary(aov.Bata1)
F.Bata1=(aov.Bata1.results[[1]]$`Mean Sq`[1])/MS_err
P.Bata1=1-pf(F.Bata1,df1=(b-1),df2=df_err)
P.Bata1
## [1] 0.0004129821
# Effect of tube size on T. hudsonicus
aov.Bata2=aov(timex~tdata.size,data=reds)
aov.Bata2.results=summary(aov.Bata2)
F.Bata2=(aov.Bata2.results[[1]]$`Mean Sq`[1])/MS_err
P.Bata2=1-pf(F.Bata2,df1=(b-1),df2=df_err)
P.Bata2
## [1] 0.0005919201
```

ANOVA Results

A two-factor between-subjects ANOVA showed that the interaction between species and tube size had a significant effect on time spent (Box-Cox transformed) (F_2,60 = 7.334, P = 0.0014). Because of the significance of the interaction, the main effects cannot be reported. An analysis of simple effects showed that there was no significant difference in time spent (Box-Cox transformed) by *T. striatus* (x̄ ± sd = <0.0001 ± <0.0001) and *T. hudsonicus* (0.1 ± 0.2108) with 0.50-inch diameter tube (F_1,20 = 2.727, P =0.4758), but every other simple effect had significance. In the case of the 0.75-inch tube, *T. striatus* spent significantly more time interacting (Box-Cox transformed) (00.50605 ± 0.4257) than *T. hudsonicus* (0.2023 ± 0.3365) (F_1,20 = 4.643, P = 0.0126). With the 1.25-inch tube, *T. hudsonicus* spent significantly more time interacting (Box-Cox transformed) (0.6613 ± 0.3557) than *T. striatus* (0.2707 ± 0.4051) (F_1,20 = 5.652, P = 0.0068). The simple effects analysis also showed that tube size had a significant effect on time spent (Box-Cox transformed) for *T. striatus* (F_2,33 = 8.189, P = 0.00129), as well as for *T. hudsonicus* (F_2,27 = 9.432, P = 0.0007). A post hoc Tukey HSD test will be conducted to further investigate these effects.

Post Hoc Tukey’s HSD Test on Transformed Data

```
TukeyHSD(aov2)
##   Tukey multiple comparisons of means
##     95% family-wise confidence level
```

```
##
## Fit: aov(formula = timex ~ tdata.species * tdata.size, data = tdatat)
##
## $tdata.species
##                 diff         lwr        upr      p adj
## red-chip 0.04415818 -0.1168132 0.2051296 00.50852283
##
## $tdata.size
##                     diff        lwr       upr     p adj
## tube.2-tube.1 0.3522727  0.1163930 00.50881523 0.0019084
## tube.3-tube.1 0.4028314  0.1669517 0.6387110 0.0003616
## tube.3-tube.2 0.0505587 -0.1853210 0.2864384 0.8642887
##
## $`tdata.species:tdata.size`
##                                 diff         lwr        upr     p adj
## red:tube.1-chip:tube.1   0.10000000 -0.31032017 00.501032017 0.9790869
## chip:tube.2-chip:tube.1  00.506051580  0.16929087 0.95174073 0.0011446
## red:tube.2-chip:tube.1   0.20238095 -0.20793922 0.61270112 0.6954339
## chip:tube.3-chip:tube.1  0.27073621 -0.12048872 0.66196114 0.3341677
## red:tube.3-chip:tube.1   0.66134560  0.25102543 1.07166577 0.0001873
## chip:tube.2-red:tube.1   0.46051580  0.05019563 0.87083596 0.0191368
## red:tube.2-red:tube.1    0.10238095 -0.32618449 00.503094639 0.9808547
## chip:tube.3-red:tube.1   0.17073621 -0.23958396 00.508105638 0.8229643
## red:tube.3-red:tube.1    00.506134560  0.13278016 0.98991104 0.0036928
## red:tube.2-chip:tube.2  -0.35813485 -0.76845501 0.05218532 0.1209915
## chip:tube.3-chip:tube.2 -0.28977959 -0.68100452 0.10144534 0.2620802
## red:tube.3-chip:tube.2   0.10082980 -0.30949037 00.501114997 0.9783115
## chip:tube.3-red:tube.2   0.06835526 -0.34196491 0.47867542 0.9963407
## red:tube.3-red:tube.2    0.45896465  0.03039921 0.88753008 0.0289980
## red:tube.3-chip:tube.3   0.39060939 -0.01971078 0.80092956 0.0708504
```

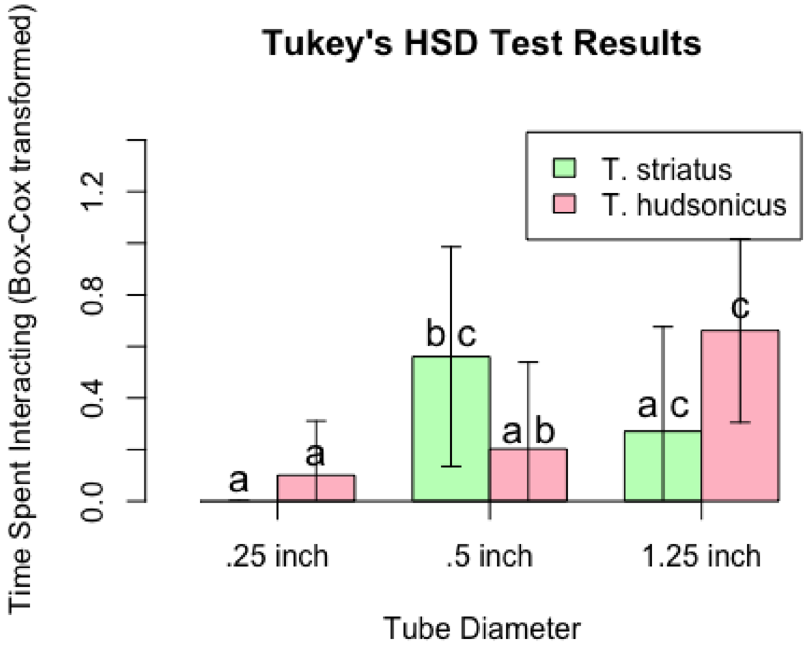
Tukey's HSD Results

A post hoc Tukey's HSD test showed fewer significant effects than the analysis of simple effects (See Table 1). It showed that *T. striatus* spent significantly more time interacting (Box-Cox transformed) with the 0.75-inch tube than with the 0.50-inch tube (P = 0.0011), but it did not spent significantly more time interacting (Box-Cox transformed) with the 0.75-inch tube than it did with the 1.25-inch tube (P = 0.2620). It also did not spend significantly more time interacting (Box-Cox transformed) with the 1.25-inch tube than it did with the 0.50-inch tube (P = 0.3341). The analysis showed that *T. hudsonicus* spent significantly more time (Box-Cox transformed) interacting with the 1.25-inch tube than with the 0.50-inch tube (P = 0.0036), and significantly more time (Box-Cox transformed) interacting with the 1.25-inch tube than with the 0.75-inch tube (P = 0.0289). It did not show a significantly greater amount of time spent (Box-Cox transformed) with the 0.75-inch tube than with the 0.50-inch tube (P = 0.9808). The analysis did not show that *T. striatus* spent significantly more time interacting (Box-Cox transformed) with the 0.75-inch tube than *T. hudsonicus* (P = 0.1209), unlike the simple effects analysis. Likewise, it did not show that *T. hudsonicus* spent significantly more time interacting (Box-Cox transformed) with the 1.25-inch tube than *T. striatus* like the simple effects analysis had, but it did come close to significance (P = 0.0708).

Bar Plot

```
# Bar Plot of Tukey HSD Results
plot.avg20=tapply(tdatat$timex[tdatat$tdata.species=="red"],tdatat$tdata.size[tdatat$
tdata.species=="red"],mean)
plot.err20=tapply(tdatat$timex[tdatat$tdata.species=="red"],tdatat$tdata.size[tdatat$
tdata.species=="red"],sd)
plot.avg10=tapply(tdatat$timex[tdatat$tdata.species=="chip"],tdatat$tdata.size[tdatat
$tdata.species=="chip"],mean)
plot.err10=tapply(tdatat$timex[tdatat$tdata.species=="chip"],tdatat$tdata.size[tdatat
$tdata.species=="chip"],sd)
plot.avg30=c(plot.avg10,plot.avg20)
plot.err30=c(plot.err10,plot.err20)
barplot30=barplot(plot.avg30[order(tdatat$tdata.size)],width=c(4.2,4.2),space=c(-
10.75,0),legend=legendtext,beside=T,axisnames=T,ylab="Time Spent Interacting (Box-Cox
```

```
transformed)",xlab="Tube Diameter",ylim=c(0,10.50),xlim=c(-9,25),main = "Tukey's HSD
Test Results",col=mycols,xaxt="n")
nlo30=plot.avg30-plot.err30; nhi30=plot.avg30+plot.err30
segments(x0=barplot30, x1=barplot30, y0=nlo30[order(tdatat$tdata.size)],
y1=nhi30[order(tdatat$tdata.size)])
segments(x0=barplot30-0.50, x1=barplot30+00.50, y0=nhi30[order(tdatat$tdata.size)],
y1=nhi30[order(tdatat$tdata.size)])
segments(x0=barplot30-0.50, x1=barplot30+00.50, y0=nlo30[order(tdatat$tdata.size)],
y1=nlo30[order(tdatat$tdata.size)])
axis(side=1,labels=c(".25 inch","0.50 inch","1.25 inch"),at=c(-3.16,8.4,19.95))
text(barplot30[1],plot.avg30[1]+.08,"a",cex=1.3)
text(barplot30[2],plot.avg30[1]+.18,"a",cex=1.3)
text(barplot30[6]+5.25,plot.avg30[2]+.1,"b c",cex=1.3)
text(barplot30[8]+8.44,plot.avg30[1]+.28,"a b",cex=1.3)
text(barplot30[25]+100.50,plot.avg30[1]+.37,"a c",cex=1.3)
text(barplot30[30]+8.4,plot.avg30[1]+0.752,"c",cex=1.3)
```



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