Received: 25 May 2024 | Revised: 22 April 2025 | Accepted: 13 May 2025

DOI: 10.1111/csp2.70084

CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access

WILEY

Which design is better? A lifecycle approach to the sustainable management of artificial habitat-structures

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Abstract

This article develops a lifecycle-based design approach to sustainably provide artificial tree hollows for habitat restoration. It addresses the growing reliance on nest boxes to mitigate impacts from development, forestry, agriculture, and extreme weather events. Although conservation efforts frequently use artificial hollows, their effectiveness and durability remain uncertain. This uncertainty underscores the need for designs that consider environmental, logistical, and economic factors over long periods. Our approach integrates knowledge of how natural hollows form and persist with analyses of how artificial structures function over time to create innovative designs and evaluate their sustainability. We applied this approach to a case study in a storm-damaged forest in northern Italy, focusing on boreal owls (*Aegolius funereus*) as the target species. Our modeling assessed the impact of supplying artificial hollows for 50 years at 741 nesting sites, comparing prototypes made from laser-cut plywood, 3D-printed plastic, and mycelium blocks. The analysis showed that mycelium offered the most environmentally sustainable option according to our criteria, while plastic remained the most cost-effective over time. Replacing plastic with mycelium could reduce carbon emissions by 75%, energy consumption by 78%, and waste generation by 81%, but would increase monetary costs by 15.5%. Plywood incurred costs similar to plastic and mycelium but would require substantial design and manufacturing improvements to compete effectively in other criteria. These findings clarify the environmental trade-offs of different design choices and could guide the development of sustainable conservation strategies in other ecosystems.

KEYWORDS

artificial hollow, biodiversity conservation, boreal owl, computer-aided design, interspecies design, lifecycle analysis, more-than-human design, multispecies design, nest box, sustainability

1 | INTRODUCTION

Globally, thousands of species depend on tree hollows for shelter and reproduction (Van Der Hoek et al., 2017). Many animals cannot create their own hollows and instead rely on cavities in trees excavated by birds such as woodpeckers, insects such as termites, or decay-causing organisms including fungi and bacteria (Gibbons & Lindenmayer, 2002). These "natural" ("bio-induced" or "biogenic") tree hollows can take decades or even centuries to develop (Vesk et al., 2008). Today, hollows are in short supply in many places due to human activities including urban encroachment (Davis et al., 2013), agriculture intensification (Lindenmayer, 2017), logging (Lindenmayer et al., 2012), and the abandonment of traditional silviculture such as pollarding that can promote hollow formation (Sebek et al., 2013). Existing practices often interrupt the supply of hollows when management removes old trees and does not plant new ones, or when planted trees are too young to supply hollows (Manning et al., 2012). Resulting scarcity puts dependent wildlife at risk of decline and even extinction (Penton et al., 2021). In response, conservationists provide "artificial" ("human-made" or "anthropogenic") hollows. For example, nest boxes can provide critical habitat structures for birds (Stojanovic et al., 2023) and mammals (Goldingay et al., 2020) when the supply of natural hollows is absent or insufficient (Cockle et al., 2010; Goldingay & Stevens, 2009). However, artificial hollows can vary in their effectiveness at supporting biodiversity (Dicks et al., 2021; Littlewood et al., 2020) while also posing risks to bird health and reproduction (Zhang et al., 2023). Expensive, ineffective, harmful, or short-lived implementations have raised doubts about the value of nest boxes (McKenney & Lindenmayer, 1994; Le Roux et al., 2015, 2016; Lindenmayer et al., 2017; Rueegger et al., 2019; Brown et al., 2021), prompting calls for research to address the gap in knowledge needed for better designs (Thompson et al., 2023).

Another key challenge is understanding the broader implications of implementing artificial hollows across temporal and spatial scales. The economic and environmental implications of artificial hollows as conservation tools are likely to increase. For example, there are plans to create one million hollows in fire-damaged forests in Australia (Luu, 2021) and 300 million plastic hollows on utility poles in the United States (Schultz, 2018). There are already several million nest boxes within domestic gardens in the United Kingdom (Davies et al., 2009). Further research is necessary to understand the systemic impacts of such large-scale interventions. Some studies estimate the economic costs of nest-box programs over a span of more than 150 years (McKenney & Lindenmayer, 1994; Spring et al., 2001). Others look at sustainable materials (Gunnell et al., 2010) including recycled plastic (McComb et al., 2021), salvaged industrial pipes (Groom, 2010), and repurposed packaging (González-García et al., 2011). However, to our knowledge, systematic modeling that considers environmental, economic, and multiple other criteria is not available.

This article responds to calls for better management of artificial hollows over long periods and on landscape scales (Gibbons & Lindenmayer, 1996; Manning et al., 2012; Valera et al., 2019; Cowan et al., 2021; Watchorn et al., 2022; Thompson et al., 2023; R. D. Crawford & O'Keefe, 2024). Wildlife response serves as the cardinal metric for successful design but cannot solely define the feasibility, sustainability, or resilience of a proposed system. There is a need for systematic, numerical methods to compare and assess different potential designs under complex and uncertain conditions. For example, what are the consequences of installing hundreds of plywood boxes that may break after a few years versus plastic alternatives that may not biodegrade for centuries? When selecting a design, how does one prioritize sturdiness over biodegradability, or simplicity of construction over ease of installation?

Our research aims to integrate state-of-the-art technologies that support innovative engineering methods, enabling the creation of novel shapes, materials, and functional properties. Algorithmic and automated generation of digital or fabricated prototypes facilitates rapid iterations that adapt to structural requirements and performance targets. For instance, numerically expressed design constraints can incorporate data from laser scans with habitat features identified by artificial intelligence and informed by observations of animal behavior, as demonstrated in recent analyses of mature trees (Holland et al., 2024). These advancements enable iterative integration of feedback into design and manufacturing, promoting continuous improvement. The ultimate objective of this research is to leverage this potential to develop systems capable of supplying hollows in the required numbers in a cost-effective, environmentally sustainable, resilient, and adaptable manner. We propose a "lifecycle approach" that unifies the design, supply, and assessment of hollows, demonstrating its use to stimulate the development and comparison of novel designs, guide future research directions, and support land management.

2 | APPROACH

The "lifecycle approach" integrates biological and technological understandings of lifecycles to develop a sustainable supply of hollows, whether natural or artificial.

In biology, the concept of a lifecycle, closely related to life history and ontogeny, describes the progression of an organism through stages such as a single fertilized cell, growth and development, maturity, reproduction, senescence, and death (Bonner, 1993). Researchers can use insights from these biological lifecycles to enhance design processes aimed at supporting biodiversity (Temmink et al., 2021; Weisser & Hauck, 2017). The notion of "cycles" also applies to ecosystems like forests, wetlands, and coral reefs, encompassing phases such as growth, maturity, disturbance, and succession. Within ecological systems, a cycle represents a sequence of natural processes that recur over time and sustain ecosystem characteristics. The cycle of tree hollows involves the growth, aging, and decay of trees, as well as environmental factors such as fire, storms, animal activity, and human interventions. For example, biodiversity-focused management of commercial forests considers harvesting cycles alongside stages of regeneration, development, and maturity (Kraus & Krumm, 2013). Models in forest management simulate biological cycles of natural hollows, tracking their formation in a tree through to their eventual decomposition (Ball et al., 1999). The concept of "nest webs" connects biological lifecycles of tree hollows to the species that use them. This approach to forest management helps promote resilience and biodiversity by modeling interactions between hollow producers, such as woodpeckers, and non-excavating users ("secondary cavity nesters"), including songbirds, ducks, raptors, and mammals (for the concept of nest webs in management, see Martin & Eadie, 1999; Ibarra, Cockle, et al., 2020). To make comparisons with technological lifecycles easier, and based on terminology used for hollow-bearing trees (Ball et al., 1999), we group biological stages under: formation, senescence, decomposition, and recruitment (Figure 1).

In design and engineering, lifecycle analysis (cf. cradle-to-cradle and circular economy) helps assess the environmental impacts associated with activities, products, nations, companies, and buildings (Bjørn et al., 2020; Curran, 1993). We consider technological cycles of artificial hollows using terms of lifecycle analysis: "cradle," "gate," and "grave" (Figure 1). "Cradle" includes extracting materials, processing them, and manufacturing products. "Gate" refers to the point when processed and packaged materials leave the factory gate. "Grave" describes the phase when users discard the product at the end of its "useful lifespan" (Kokare et al., 2023). Technological lifecycles provide benchmarks for sustainability that go beyond the reduction of harm and can lead to actions that minimize or even eliminate resource depletion, energy use, pollution, and landfill waste (Muralikrishna & Manickam, 2017), while protecting biodiversity (Winter et al., 2017) and restoring ecosystem services (Liu & Bakshi, 2019). Circularity can occur through biological cycles, where organic materials return to and replenish the biosphere, or through technological cycles, where synthetic materials circulate in a closed-loop system of manufacturing, maintenance, reuse, or recycling (Kopnina, 2018). Examples from marine environments, such as artificial reefs, highlight the utility of technological lifecycle assessments in ensuring environmental safety through maintenance and decommissioning (Suzdaleva & Beznosov, 2021). In terrestrial environments, recent research investigated the long-term dynamics of supplying natural and artificial roosting sites for birds (Holland et al., 2023). While studies on nest boxes have considered the lifecycles of target species (Stojanovic et al., 2020), the cycles of hollows remain underexplored.

By integrating aspects of biological and technological cycles (Figures 1 and 6), our approach aims to: (1) utilize eco-friendly materials, (2) adopt production methods that involve nonhuman organisms, (3) align structural characteristics with the needs of target species, (4) support shared use by multiple species, (5) facilitate upkeep, and (6) support both end-of-life strategies and the supply of replacements. This bioinformed approach seeks to replicate properties and apply processes found in ecological systems (Ng et al., 2021), addressing calls for hollow provisioning strategies informed by biological interactions (Lindenmayer, 1996).

3 | METHODS

To explore the potential of a lifecycle approach, we conducted a "design experiment," a method that combines theoretical inquiry with practical experimentation to develop innovative solutions. It involves iterative designing, testing, and refining interventions in real-world settings (Collins et al., 2004; Felson & Pickett, 2005). The purpose of this experiment is to prototype numerically defined, algorithmically adjustable, measurable and comparable systems that can improve with feedback.

To provide such characteristics, the design experiment:

i. defined a brief that responded to a need to replace woodpecker hollows used by secondary cavity nesters in a storm-damaged forest (Section 3.1);
ii. designed one lifecycle of an aspirational artificial hollow for the damaged area to illustrate opportunities offered by design innovation (Section 3.2) and enable subsequent development (Section 5.1);
iii. constructed three versions of this prototypical design using computer-assisted techniques to provide scope for comparative assessment (Section 3.3);

FIGURE 1 Biological, technological, and integrated cycles with stages named using terms from disciplinary literature. Image by the authors.

iv. estimated the economic and environmental implications of supplying these versions over timescales necessary for natural hollows to recruit (Section 3.4); and
v. compared the economic and environmental implications of supplying the numbers of hollows necessary for the damaged area (Section 3.5).

3.1 | Design brief

In 2018, a large windstorm named Vaia hit northern Italy, damaging more than 42,000 hectares of forest (Chirici et al., 2019). We focused on the Trento province, where the storm affected approximately 20,000 hectares (Provincia Autonoma di Trento, 2022), consisting predominantly of Norway spruce (*Picea abies*) (Provincia Autonoma di Trento, 2019). Our study site was the Paneveggio-Pale di San Martino Natural Park, located in the eastern part of the province. Our primary target species was the boreal owl (*Aegolius funereus*), a climate-sensitive species that lives in the study area (Brambilla et al., 2020). Boreal owls typically nest in tree hollows excavated by woodpeckers (Brambilla et al., 2013) but also use human-supplied hollows (Williams et al., 2021). Many of the fallen trees had hollows made by black woodpeckers (*Dryocopus martius*), which provided nesting and sheltering sites for multiple species of mammals and birds including boreal owls (Marchesi et al., 2020). Logging after the storm has removed even more trees with hollows (Bettega et al., 2024). The need for large-scale and long-term supply of hollows made this area a suitable case study. The brief for design was to specify patterns of supply that could sustain pre-storm numbers of hollows per hectare.

3.2 | Prototypical design

To prototype one lifecycle of a hollow, we applied the approach introduced in Figure 1 to the development and materialization of an adjustable design (Figure 2). Building on previous work (Roudavski & Parker, 2020; Parker et al., 2022), we utilized computer-aided design algorithms to generate geometries informed by characteristics of natural habitat-structures. These techniques enable innovative features that open possibilities for addressing emerging challenges, such as climate change or use by non-target species, while suggesting directions for further collaborative research.

The primary intention of this design was to support secondary cavity nesters such as boreal owls, with space to accommodate an incubating mother and 2 to 6 eggs (Camprodon et al., 2020). Its geometry offers provisions for owl behavior and incorporates features specific to the study area. The hollow resembles bracket mushrooms, which create an awning above some natural hollows and serve as roosting sites for boreal owls. Surface patterns mimic mushroom gill structures, with horizontal ridges inside to assist climbing and vertical patterning outside to channel water away from the entrance. Similar to bryophyte-supporting woodpecker hollows and trees in the study area, the design incorporates bio-receptive features to promote moss and lichen growth. Moisture-retaining pores are more frequent in shadier, wetter areas, identified through computer simulations of water runoff (di Catemario Quadri, 2021; Piker, 2019) and solar-irradiation analyses (Roudsari & Pak, 2013). The tapered form facilitates easy exiting and water drainage. This prototypical design enabled us to concretize aspirations of the lifecycle approach and explore the potential of emerging technologies. It provided a foundation for assessment (Section 3.4 and 3.5) and design iteration (Section 5.1).

3.3 | Versions for comparison

To explore systemic implications of the prototypical design, we developed three versions that combine different materials and manufacturing approaches. Material performance can significantly influence both functional characteristics and the environmental impact of habitat structures. Computer-aided manufacturing of biobased and living materials, often referred to as "biomaterials," offers notable advantages in both areas (Carcassi & Ben-Alon, 2024; Stuart-Fox et al., 2023). We explored mycelium as one possible option. Mycelium, the root-like structure of fungi, increasingly features in architecture, product design, and packaging due to its versatility, lightweight quality, shock absorption, acoustic properties, thermal insulation, and biodegradability (Jose et al., 2021; Manan et al., 2022; McGaw et al., 2022). As a construction material, mycelium grows through and binds organic substrates such as residues of agricultural crops, woodchips, hemp, or sawdust (Elsacker et al., 2020; Gough et al., 2024).

We chose plywood, plastic, and mycelium to compare widely used materials with innovative options (Figure 3). The plywood prototype consisted of thin wooden layers bonded with adhesive (Müller et al., 2023). The plastic prototype utilized polylactide

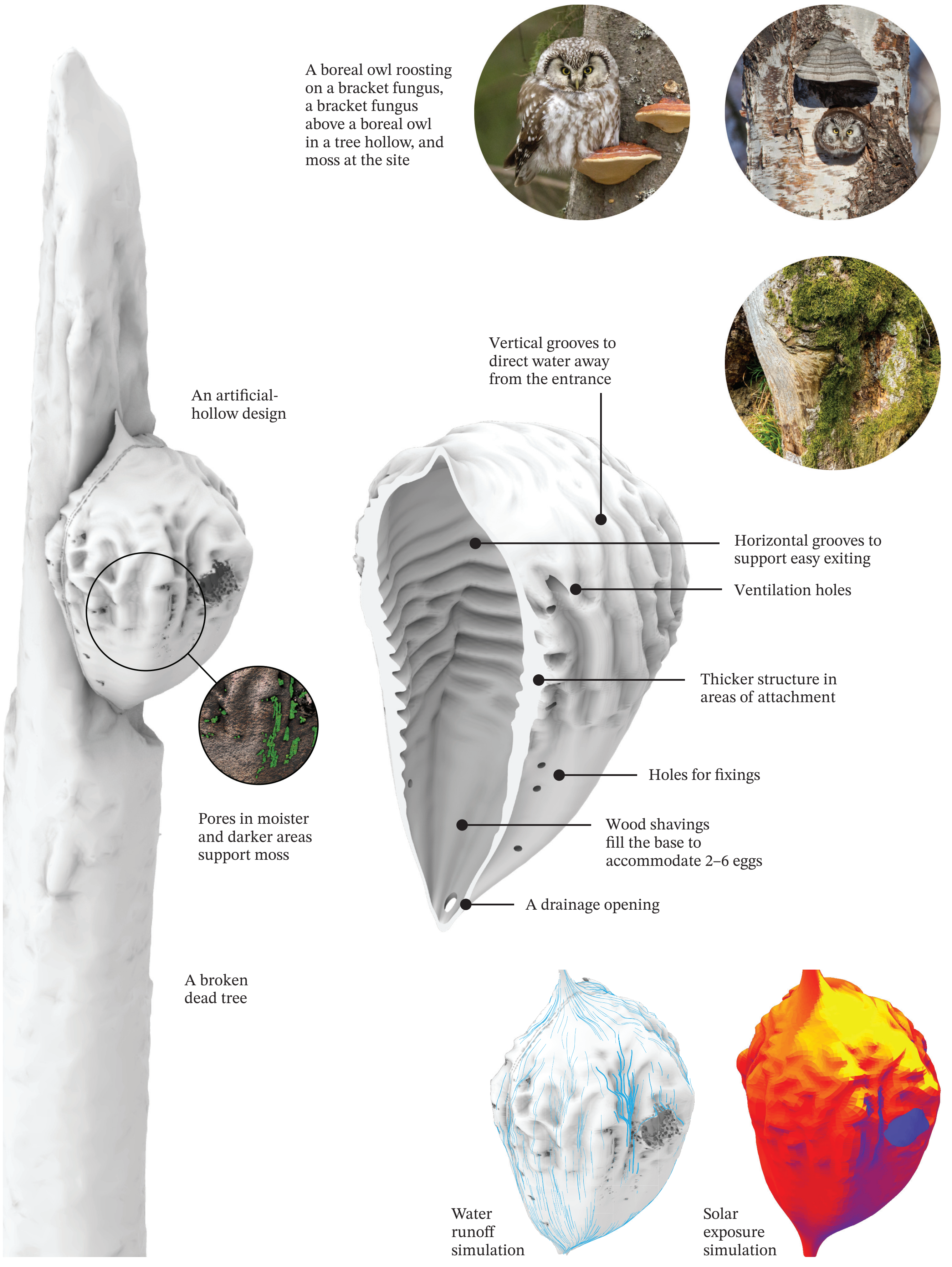

FIGURE 2 A design of an artificial hollow informed by the behavior of the target species, site analysis, and simulations of environmental conditions. Image by the authors. Photo of a boreal owl roosting on a mushroom by Tobias Svensson. Photo of a mushroom above a boreal owl by Gary Schultz.

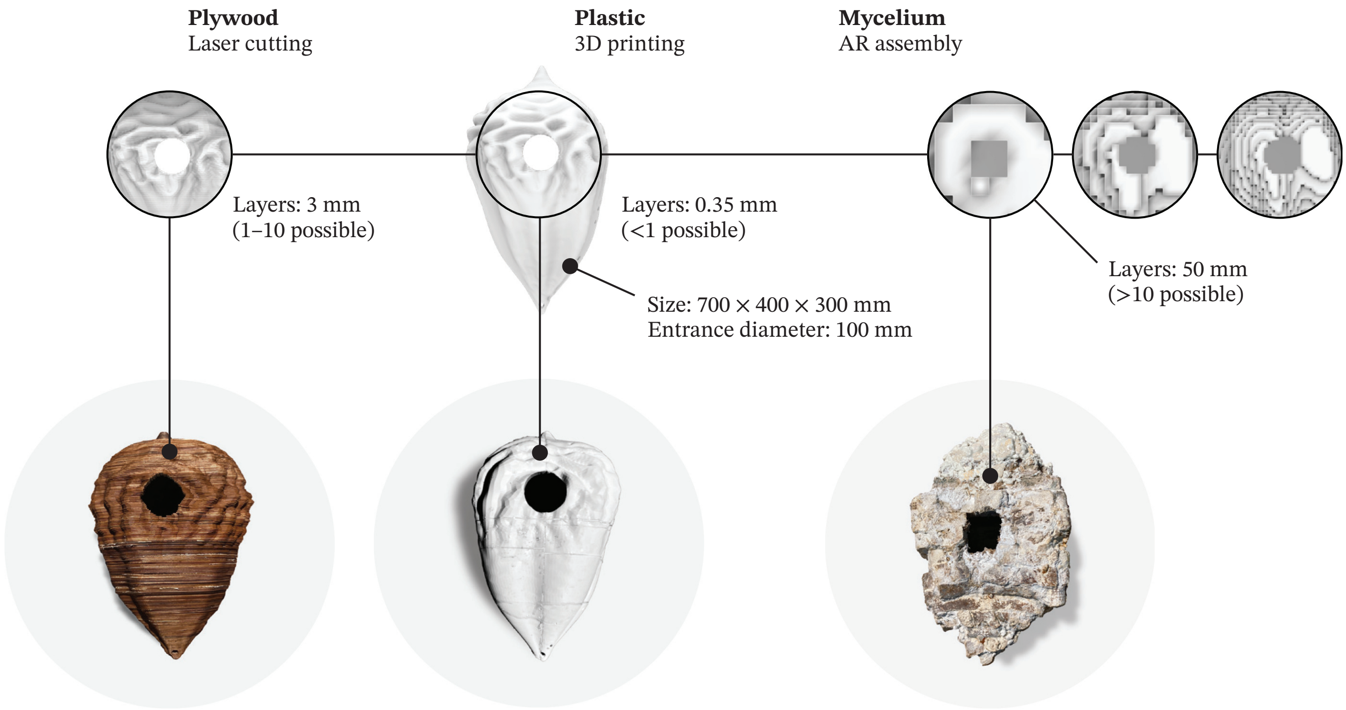

FIGURE 3 Materials, manufacturing methods, and dimensions of the prototypes: Plywood assembled from laser-cut sheets, 3D-printed plastic, and mycelium-based composites assembled using augmented reality. The computer models (top row) show resolutions achievable with each manufacturing method and used in the prototypes (bottom row). Image by the authors.

(commonly known as PLA), a plant-based material derived from crops such as sugarcane or cassava (Morão & de Bie, 2019). The mycelium prototype incorporated commercially available reishi/lingzhi (*Ganoderma lucidum*), a fungus species native to northern Italy (Centre for Agriculture and Bioscience International (CABI), 2021; Cartabia et al., 2022).

We used a distinct manufacturing technique for each material, building on our earlier applications of computer-aided manufacturing (Parker et al., 2022; Roudavski & Parker, 2020). Our previous work developed prototypes from 3D-printed wood and hempcrete, which have been in use for over five years. That research highlighted the need for further exploration into sustainable manufacturing methods for artificial hollows.

In this study, we advanced our previous research by using computer-aided manufacturing to produce the complex shapes required for each prototype. We laser-cut plywood sheets, 3D-printed plastic components, and employed augmented reality (AR) to assemble mycelium blocks. AR assembly involves using devices like goggles or smartphones to guide component placement by overlaying a computer-generated model onto the physical workspace.

The prototypes measured 700 × 400 × 300 mm, with an entrance diameter of 100 mm, matching the dimensions of black woodpecker hollows. The layer heights, or precision levels, varied based on material availability, the limitations of each manufacturing tool, and the aim to maintain comparable assembly speeds across the different prototypes. By completing these prototypes, we verified their constructability and gathered valuable information about their material properties, costs, and logistical requirements for subsequent lifecycle analysis.

3.4 | Assessment over time

To analyze the lifecycles of the three prototypes, we estimated upfront and cumulative carbon emissions, embodied energy, monetary costs, and waste production associated with continuous supply. We calculated the costs of each prototype version over a 50-year period, aligning with the time typically required for fast-growing trees like aspen to become suitable for woodpecker hollows (Rolstad et al., 2000; Trzcinski et al., 2021; Zawadzki, 2024). Our analysis factored in the typical lifespans of artificial hollows to estimate the number of replacements needed to maintain consistent availability. For instance, maintaining supply over 50 years would require ten hollows with five-year lifespans but only two with 25-year lifespans. We refer to these replacements as "cycles," following the terminology in Lindenmayer et al. (2018).

For the analysis, we selected the most likely input values based on the properties of the prototypes we created and supplemented them with confidence ranges representing higher and lower estimates. We obtained data for volume, weight, cost, and waste directly from the physical prototypes. Estimates for lifespan, installation requirements, carbon emissions, energy use, and waste came from published studies on hollows and lifecycle analyses, including cradle-to-gate (CTG), cradle-to-cradle (CTC), and gate-to-grave (GTG). The analysis does not include fixings such as straps around the host tree.

Refer to Table 1 for the assumptions and sources of each prototype's material and manufacturing process.

3.5 | Assessment at scale

We extrapolated the values obtained from the lifecycle analysis of the prototypes over time to estimate the environmental and economic impacts of reinstating hollows lost in Paneveggio Natural Park. Storm Vaia damaged approximately 650 hectares of forest in this area (Ente Parco Paneveggio Pale di San Martino, 2021). To estimate the number of hollows lost during the storm, we assumed an average of three woodpecker-made hollows per hectare, with a confidence range of one to ten (Marchesi et al., 2020). However, the number of hollows used by secondary cavity nesters is often much lower than the number available (Trzcinski et al., 2021). To address this, our analysis focused on reinstating only those hollows likely to be suitable for secondary cavity nesters, estimated at 38% of the total (Ouellet-Lapointe et al., 2012), with a confidence range of 19% (Cockle et al., 2010) to 43% (Gibbons et al., 2002).

We included the costs of recommended annual inspections (Korpimäki & Hakkarainen, 2012) and triennial servicing (Griffiths, Lentini, et al., 2022; Saunders et al., 2023). Using standard commercial fees, we estimated costs at €20 per hollow for inspections and €34 per hollow for maintenance and servicing (Faunature, 2022).

4 | RESULTS

4.1 | Implications over time

Our lifecycle analysis revealed significant variations in the environmental and economic impacts of the prototypes, both upfront and over a 50-year span (Figure 4). In terms of carbon, energy, and waste, the mycelium prototype emerged as the most sustainable choice in both the short and long term. In contrast, the plywood prototype demonstrated higher carbon dioxide emissions, greater energy requirements, and increased waste production compared to the plastic and mycelium options. The plastic prototype, despite having the highest initial cost, showed potential to become the most cost-effective option over time due to its extended lifespan.

Callouts in Figure 4 highlight several factors that could alter the performance of the prototypes over time. For example, improvements to the plywood prototype—such as using lignin-based resins, employing renewable electricity, optimizing component arrangements to minimize material waste, and recycling or repurposing materials after decommissioning—could significantly reduce its carbon emissions. With these adjustments, our projections indicated that the plywood prototype could emit carbon at levels comparable to the plastic and mycelium options. However, its energy consumption and waste generation would likely remain high. This is attributed to the relatively high input requirements per unit and the inevitable offcuts and waste generated by laser cutting irregular shapes. For the mycelium prototypes, scaling up production and avoiding high-emission coatings could enable them to sequester nearly as much carbon as they emit, further enhancing their sustainability.

4.2 | Implications at scale

Our analysis revealed significant environmental and economic implications of reinstating hollows at scale, offering key insights for design decisions. We estimated that Storm Vaia in Paneveggio Natural Park resulted in the loss of 741 hollows suitable for secondary cavity nesters, with a confidence range of 123 to 2795. To maintain a consistent supply of this number of hollows over 50 years, replacing artificial hollows at the end of their lifespan would require 3710 (620–13,980) plywood prototypes, 1480 (250–5590) plastic prototypes, or 7410 (1230–27,950) mycelium prototypes. At this scale, plastic and mycelium options outperformed plywood in terms of carbon emissions, energy use, monetary costs, and waste production (Table 2). Choosing the most sustainable option (mycelium) instead of the cheapest (plastic) would increase costs by 15.5% (€397,180) but reduce carbon emissions by 75% (9820 kg), energy consumption by 78% (295,290 MJ), and waste generation by 81% (4150 kg) over 50 years (Figure 5). The substantial variation between design options highlights the importance of assessing the sustainability and feasibility of artificial hollows across their entire lifecycles.

5 | DISCUSSION

Our analysis showed that a lifecycle approach has the potential to clarify implications and guide design decisions for all phases of hollow production, supply, and replacement (Figure 1).

TABLE 1 Inputs for each prototype showing assumed values and possible ranges.

	Plywood: Laser cutting	Plastic: 3D printing	Mycelium: Augmented reality	Notes and assumptions
Lifespan	10 years installed (Lindenmayer et al., 1991; Lindenmayer et al., 2009). For reference, some range from 3 years (Lindenmayer et al., 2017) to 20+ years (Goldingay et al., 2018; Korpimäki & Hakkarainen, 2012; Quin et al., 2020)	25 years installed. For reference, some range from 20+ years (Groom, 2010) to 30+ years (estimated) with maintenance (Saunders et al., 2023)	5 years installed. There is uncertainty and variability in lifespan estimates, from less than a year when composted in soil (Zimele et al., 2020) to several years outdoors (Chayaamor-Heil et al., 2024; Karimjee, 2014), to possibly over a decade in building products (Akromah et al., 2024; Van Den Berg & Konings, 2019)	Actual lifespans of artificial hollows vary widely depending on factors such as weather, maintenance, and build quality
Installation	5 times over 50 years	2 times over 50 years	10 times over 50 years	Uses only one input because including lower and upper values would make resulting ranges too large and trends difficult to interpret
Volume	0.029 m^3 for 18 sheets of 3 × 600 × 900 mm plywood, with a lower range of 0.024 m^3 for 15 sheets of 3 × 600 × 900 mm plywood	0.012 m^3, ranging from 0.011 to 0.013 m^3	0.0368 m^3, with a lower range of 0.014 m^3 (using thinner walls)	Thinner walls, lower material density, or more efficient orientation of objects for fabrication can reduce volumes
Weight	6 kg, ranging from 5 to 7 kg	5 kg, ranging from 4 to 6 kg	6 kg, with a lower range of 3 kg (assuming reduced wall thickness)	Based on weights of constructed prototypes and possible reductions in material use
Carbon	1777 kg CO_2e/m^3 for outdoor plywood sourced from hardwood-production forests (R. Crawford et al., 2019) (CTG), ranging from 239 to 1831 kg CO_2e/m^3 (Müller et al., 2023)	3.3 kg CO_2e/kg (Benavides et al., 2020) (CTC), ranging from 0.27 kg CO_2e/kg (Vink et al., 2007) (CTG) to 4.5 kg CO2e/kg (Benavides et al., 2020) (CTC)	252.09 kg CO_2e/m^3 (Stelzer et al., 2021) (CTG), ranging from −39.5 kg CO_2e/m^3 (Livne et al., 2022) (CTG) to 1.72 kg CO_2e/kg (Früchtl et al., 2023) (CTG)	CO_2e is carbon dioxide equivalent, a unit to measure greenhouse gas emissions For other ranges and methods to improve performance, see (Alaux et al., 2024; Carcassi et al., 2022)
Energy	26,790 MJ/m^3 for outdoor plywood sourced from hardwood-production forests (R. Crawford et al., 2019) (CTG)	46 MJ/kg (Benavides et al., 2020) (CTC) for material, ranging from 27.2 MJ/kg (Vink et al., 2007) (CTG) to 66.66 MJ/kg (Vink & Davies, 2015) (CTG)	860 MJ/m^3 (Livne et al., 2022) (CTG), ranging from 652 MJ/m^3 (de Bruin, 2019) to 6 MJ/kg (Enarevba & Haapala, 2023) (GTG)	MJ is megajoules. Includes the energy required to produce the material as well as the energy required to operate machinery (e.g., laser cutters)
	Assuming 55.22 kWh, ranging from 31.42 to 74.89 kWh (Kellens et al., 2014) for 2 h cutting	31.8 MJ/kg (Song & Telenko, 2017) for printing, with a lower range of 1 kWh/kg (Cerdas et al., 2017)	0.02 kWh for 1 full charge of phone/tablet (see energy providers such as Engie)	
Cost	€436, ranging from €369 to €469	€1039, ranging from €837 to €1273	€302, ranging from €235 to €335	Uses euro with some conversions from other currencies, rounded to nearest 10 in Results. Includes costs of materials,

(Continues)

TABLE 1 (Continued)

	Plywood: Laser cutting	Plastic: 3D printing	Mycelium: Augmented reality	Notes and assumptions
				assembly, and installation. Assumes installation costs of €34 (ladder, see Faunature, 2022) to €67 (arborist, see Bainbridge et al., 2018, 9)
Waste	18.07 kg for offcuts + hollow weight, ranging from 9.16 kg for offcuts only to 19.07 kg, assuming 600 kg/m^3 weight of plywood (Parthiban et al., 2019)	6.53 kg (9% of hollow weight during manufacture + hollow weight), ranging from 0.36 kg (30.6% of hollow weight) to 8.08 kg (34.6% of hollow weight during manufacture + hollow weight) (Song & Telenko, 2017)	7.97 kg for substrate bags and foil (Stelzer et al., 2021)	Includes manufacturing waste and disposal of hollows Considers only waste to landfill. Lower limits assume recycling or repurposing at end of life Assumes recycling of cardboard packaging

5.1 | Design opportunities

The design in Figure 6 explores ways to further enhance the potential of the mycelium prototype to highlight opportunities for bioinformed designing. To describe the opportunities emerging from the complete and closed cycle introduced in Figure 1 (bottom row), Figure 6 considers possibilities in the production (stages 1–2), supply (stages 3–4), and sustainment of hollows (stages 5–6).

5.1.1 | Production

The design explores the possibility to source spores or fungal samples locally to cultivate mycelium using organic debris (McBee et al., 2022), much like termites construct nests with soil and nearby materials (Genise, 2017). The use of local strains can reduce biosecurity risks associated with introduced species (Van Den Brandhof & Wösten, 2022) and reliance on local substrates can decrease resource depletion and pollution (Vandelook et al., 2021).

Algorithmic approaches can create structures that emulate natural hollow formation through interspecies interactions (Figure 6, 2). For example, birds such as woodpeckers form symbiotic relationships with decay-causing fungi (Elliott et al., 2019; Jusino et al., 2016). Similarly, biofabrication delegates aspects of design, construction, and maintenance to nonhuman agents (Andréen & Goidea, 2022). These approaches excel in handling variable, non-standardized materials and structures that are beyond the capabilities of mass-production industrial techniques. This adaptability is particularly advantageous in scenarios where industrial manufacturing is energy-intensive, costly, polluting, or limited by geometric and functional constraints.

With further development, mycelium-based composites could replicate the stable microclimates of living tree hollows (Griffiths, Robert, & Jones, 2022; Strain et al., 2021) or the optimal conditions of mounds maintained by termites (Dechmann et al., 2004; Sanchez-Martinez & Renton, 2009). Researchers commonly apply heat treatment to harden the structure, hoping to enhance durability, slow biodegradation, increase resistance to water, and improve fire retardance (Gough et al., 2024; McGaw et al., 2022). By contrast, structures made from living mycelium promise advantages such as hygiene benefits, reduced energy consumption, and self-repair capabilities (Elsacker et al., 2023). However, approaches that avoid heat treatment can introduce new risks that include pathogen spread, contamination, and unintended colonization of sensitive ecosystems (Heilmann-Clausen et al., 2015). This is because dried mycelium structures that have not been treated with heat can reactivate and continue growing. Designers must carefully balance these ethical, biological, and technical considerations. Identifying reliable methods of production that minimize risks without undermining beneficial properties remains a key challenge and a priority for future research.

5.1.2 | Supply

Biomaterials like mycelium can produce functional shapes tailored to suit local species (Figure 6, 3). This precision comes with flexibility that allows iterative refinement of features, such as entrance shapes or feeding

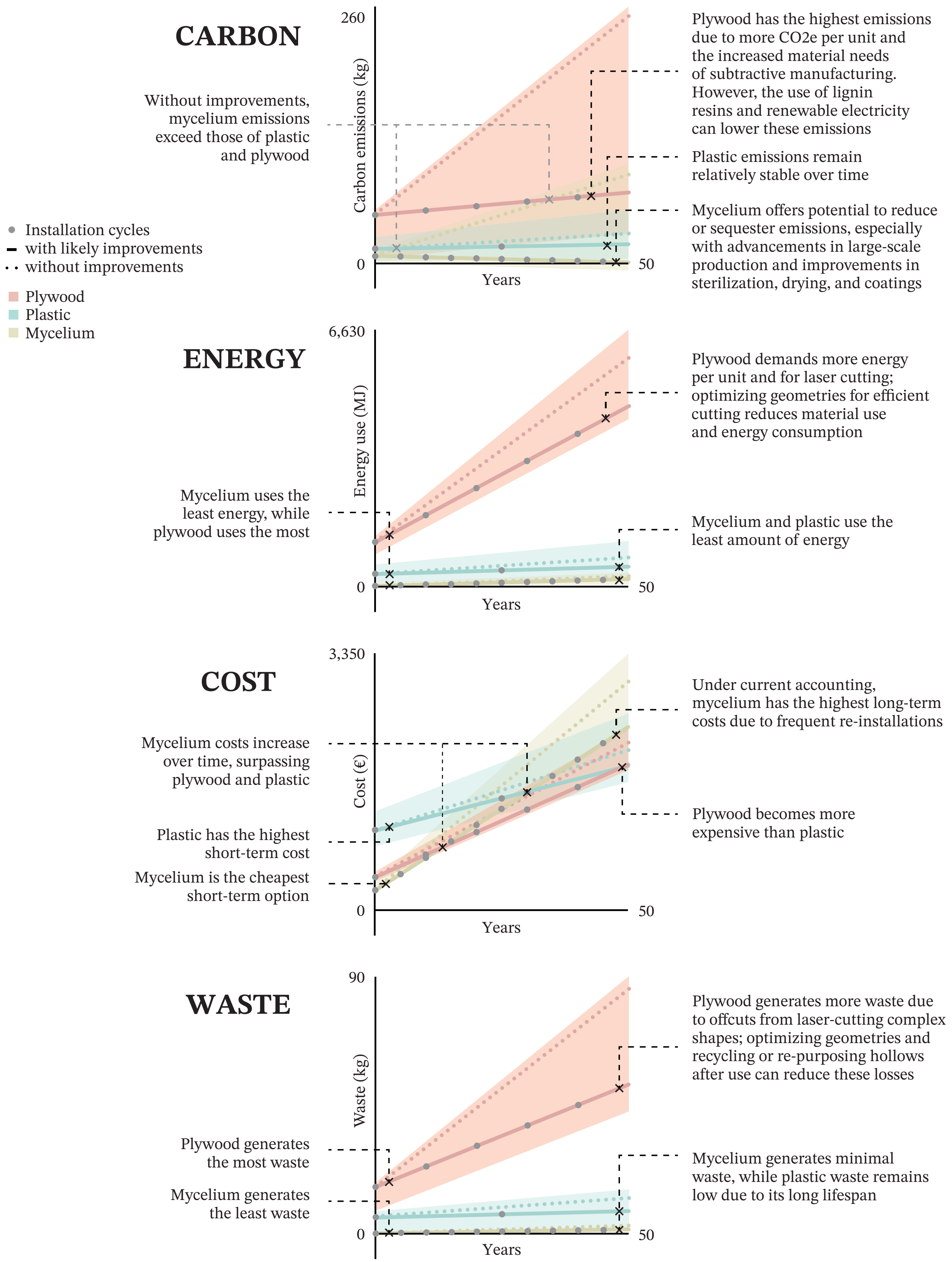

FIGURE 4 Estimates of carbon emissions, energy use, monetary costs, and waste production. Gray dots indicate moments when hollows are replaced. Dashed lines represent projections based on the initial prototypes without improvements. Solid lines show projections with feasible, near-term improvements. Colored areas represent confidence ranges. Image by the authors.

TABLE 2 A comparison estimating total carbon emissions, energy use, monetary costs, and waste production from supplying, maintaining, monitoring, and replacing artificial hollows.

	Number of hollows	Carbon (kg CO_2e)	Energy (MJ)	Cost (€)	Waste (kg)
Plywood: Laser cutting	3710 (620–13,980)	55,610 (9270–209,760)	3,474,690 (579,110–13,106,270)	2,573,370 (428,900–9,706,570)	40,530 (6760–152,880)
Plastic: 3D printing	1480 (250–5590)	13,030 (2170–49,140)	379,540 (63,260–1,431,600)	2,548,550 (424,760–9,612,940)	5110 (850–19,260)
Mycelium: Augmented reality	7410 (1230–27,950)	3200 (530–12,090)	84,250 (14,040–317,800)	2,945,720 (490,950–11,111,060)	960 (160–3610)

platforms, based on observed animal behavior. Beyond precision, artificial hollows can replicate natural ecological roles, hosting diverse species across trophic levels (Figure 6, 3). For instance, a single woodpecker hollow may support fungi, bryophytes, and up to seven vertebrate species (Cockle et al., 2019; Larrieu et al., 2018). Our research aims to accommodate such sharing (Figure 6, 4), acknowledging that aesthetics are important for both target species and human stakeholders (Parker et al., 2022). Biological communities within hollows also impact the health of incubating birds and chicks, with decay-causing organisms playing a crucial role in decomposition and nutrient recycling (Gibbons & Lindenmayer, 2002). To enhance these opportunities, surfaces of artificial hollows can promote moss and lichen growth, with shadier and wetter areas identified by computer simulations. 3D scanning informs the context-specific simulations through precise positioning of hollows on both dead and living trees (Roudavski & Parker, 2020) (Figure 6, bottom right).

5.1.3 | Sustainment

Hollow maintenance can include cleaning, repair, and modifications to suit new users (Figure 6, 5). Mycelium-based materials demonstrate potential for self-repair and allow adjustments such as modifying entrances or cavity sizes based on observed needs. Self-repairing properties of mycelium (Elsacker et al., 2023; McBee et al., 2022) mimic termite nest maintenance behaviors, such as sealing entrances, repairing external layers, and rebuilding after damage (Facchini et al., 2020; Lubin et al., 1977). Drying the material during manufacturing preserves the mycelium in a dormant state, allowing it to resume growth under favorable conditions (Appels & Wösten, 2021; McBee et al., 2022). This approach reduces material degradation (Chayaamor-Heil et al., 2024; Le Ferrand, 2024) and offers flexibility by adjusting substrate density or applying protective coatings to meet site-specific needs (Gan et al., 2022).

All hollows, natural or artificial, have a limited lifespan, after which their materials return to the environment and assume new ecological roles (Figure 6, 6). This process can be beneficial with biodegradable materials or harmful with polluting products. Land managers can remove or replace hollows once they become unsuitable for target species or leave them to serve as habitats for invertebrates. For instance, black woodpecker hollows have an average lifespan of 18 years (Wesołowski, 2011), while spruce-tree hollows in the study area typically last only four years—a duration comparable to some nest boxes (Lindenmayer et al., 2017). These short lifespans

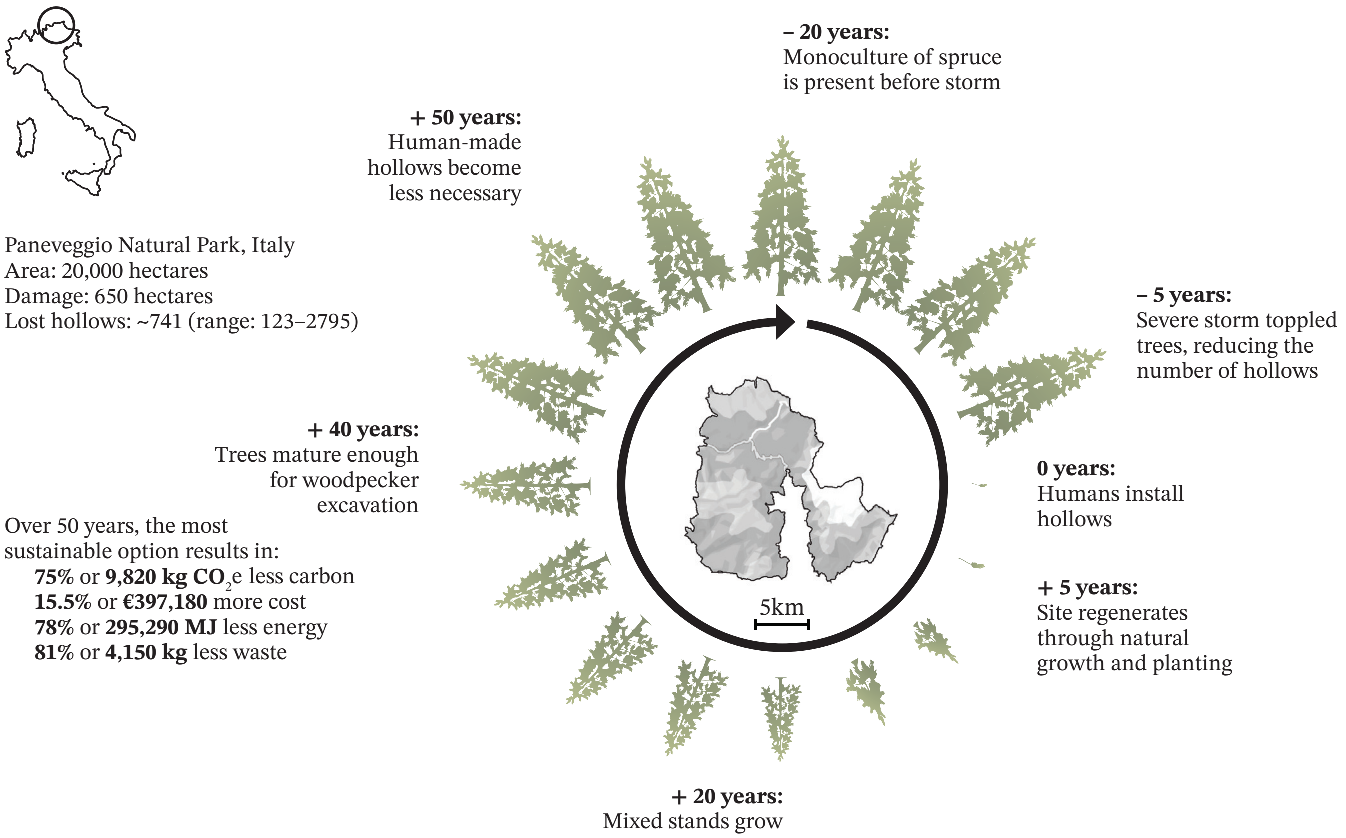

FIGURE 5 Implications of selecting the most sustainable design option (mycelium) over the cheapest (plastic) to maintain the supply and servicing of 741 hollows over 50 years at Paneveggio Natural Park, Italy.

highlight the need for strategies that address end-of-life scenarios for artificial hollows. Mycelium-based designs use biodegradable materials that can reintegrate naturally into the soil (Van Wylick et al., 2022; Gough et al., 2024). Like tree trunks with woodpecker hollows that fall and support species closer to the forest floor, a mycelium hollow on the ground could continue supporting biodiversity. It may provide habitats for organisms such as insects, snakes, lizards, and plants, extending its ecological value even after ceasing to function as a bird nest. As one structure decomposes and returns to the soil, another can emerge, leveraging the natural affordances of the site (Figure 6, 1).

So far, we have installed a single mycelium-based prototype as a proof of concept and a tool for learning (Figure 6). In 2023, a redstart *Phoenicurus* sp. occupied the hollow. However, additional field tests involving a larger number of hollows and varied designs will be necessary to gain an understanding of wildlife responses.

5.2 | Production of individual hollows

Our design experiment highlights the potential of a lifecycle approach to create artificial tree hollows that better replicate the beneficial properties of natural hollows. Mycelium offers a promising alternative that can use local, renewable, and low-waste materials. Figure 6 outlines a process where mycelium hollows can avoid practices that involve cutting trees, using plastics or metals that generate persistent waste, extracting materials from extensive land areas, or relying on global supply chains. This approach remains untested at scale and requires further research, planning, and practical testing. Most current manufacturing methods for mycelium-based composites rely on plastic molds, laboratory processing, and production systems that transport material components across wide geographical areas. These fragmented systems complicate efforts to track environmental impacts and assign responsibilities throughout the production process. Future assessments should aim to minimize these drawbacks and improve the sustainability and practicality of mycelium-based designs.

A lifecycle approach also opens avenues to explore more ambitious conservation goals. For example, designs using mycelium could allow birds like kookaburras *Dacelo* sp. and pardalotes *Pardalotus* sp. to shape their own nesting spaces, much like they do in soft substrates such as soil or termite nests. Additionally, these designs could facilitate nutrient cycling, where excrement,

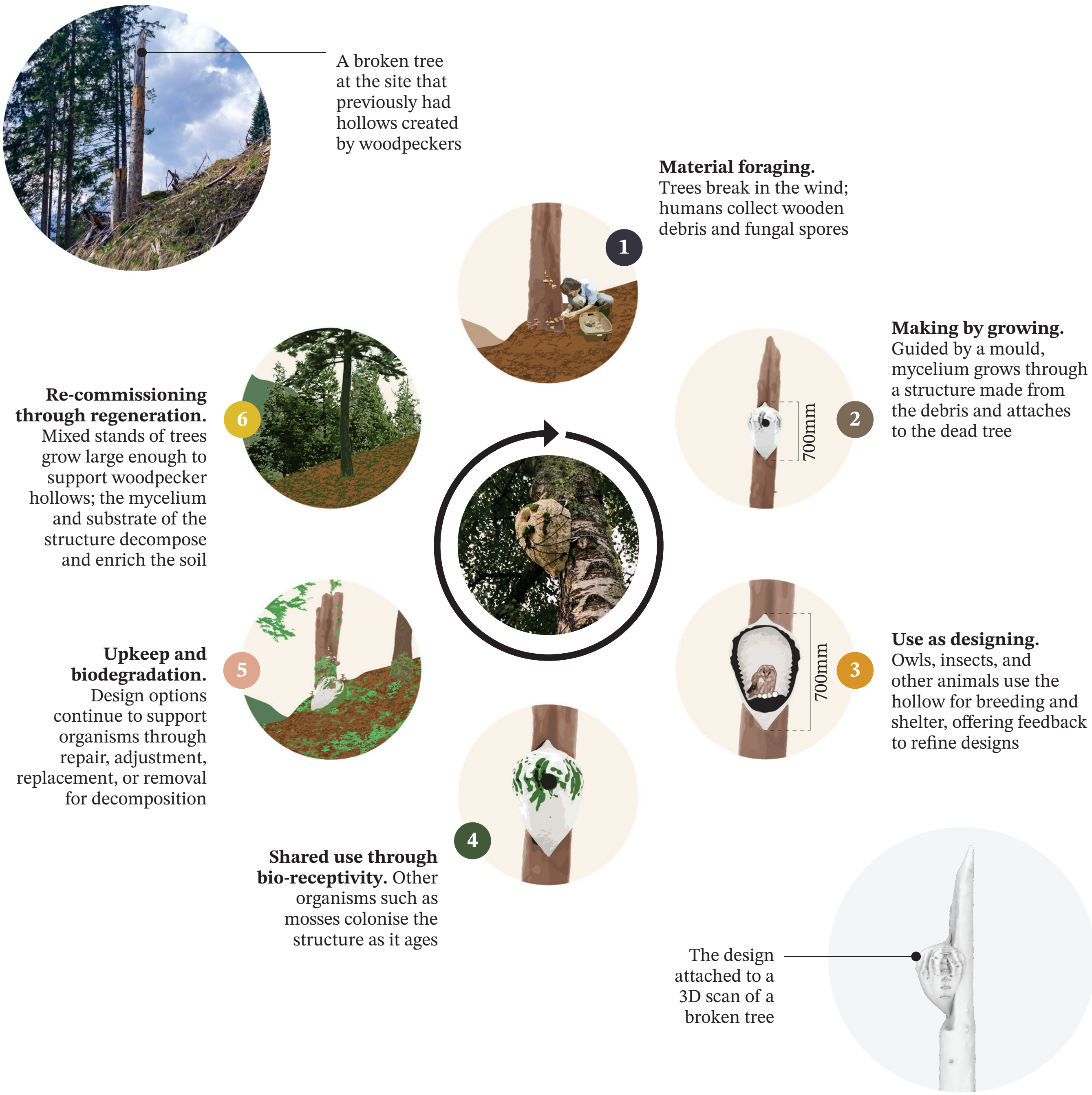

FIGURE 6 One cycle of an artificial hollow informed by the cycles of natural hollows. Image by the authors.

animal remains, and woody debris decompose into materials that support egg incubation and raising young (Lindenmayer et al., 2018). Such conditions may encourage beneficial bacteria that signal nest quality, influence uptake, and promote the health of inhabitants (Díaz-Lora et al., 2019). These possibilities highlight how a lifecycle approach can inspire innovations beyond conventional plywood boxes, guiding future research and design.

Further research is necessary to formulate practical recommendations for land managers. Field tests must confirm the suitability of mycelial substrates for vertebrate nesters, such as the boreal owl, and assess their compatibility with diverse communities of invertebrates, fungi, and bacteria commonly found in natural hollows (Wetherbee et al., 2022). Addressing feasibility challenges is also critical. Standardizing mycelium-based materials, scaling production, accounting for variable properties over time, and growing mycelium in situ without a controlled environment present significant hurdles (Bitting et al., 2022; Le Ferrand, 2024; Sun, 2024). Furthermore, mycelium-based designs require careful management to prevent the fungus from consuming the substrate entirely, exhausting nutrients, or attracting potentially pathogenic organisms (Le Ferrand, 2024).

5.3 | Supply of multiple hollows

Lifecycle assessments make the environmental consequences of design choices clearer, offering more transparent methods to compare proposed hollow supply strategies. These assessments can help conservation managers advocate for more sustainable and effective solutions. Practitioners with limited budgets may prioritize maximizing impact by installing a larger number of less expensive hollows. However, our analysis highlights the importance of considering the long-term consequences of supplying multiple cycles of hollows, not just the initial costs. For instance, while plywood is initially 43% cheaper than plastic, it becomes 4.84% more expensive over a 50-year supply period at our study site. Additionally, we project the mycelium prototype to use only 22% of the energy, emit 25% of the carbon dioxide, and produce 19% of the waste compared to the plastic prototypes over the same period. These findings underscore the value of incorporating lifecycle thinking into decision-making for artificial hollow designs.

Our approach to quantifying environmental benefits could attract greater investment in sustainable designs and encourage developers to adopt more ambitious standards when using artificial hollows. For example, analyses of long-term impacts can encourage approaches that seek to minimize carbon emissions and energy consumption of materials such as plywood. The use of wood from sustainably managed plantations, processing with renewable energy, and bonding with lignin-based resins can achieve such improvements. Our modeling informs design decisions by balancing costs, material efficiency, and structural integrity. This lifecycle approach offers a holistic assessment of potential impacts, providing a path towards designs that suit wildlife and are sustainable.

Our approach could also introduce further scrutiny to nature offset programs that developers are legally required to implement to counteract environmental damage from construction even if the effectiveness of these programs remains contested (Lindenmayer et al., 2017; Maron et al., 2025; Moilanen & Kotiaho, 2021; Souza et al., 2021). In addition to mitigation, our approach can support rewilding and net–gain strategies, which aim to leave biodiversity in a measurably better state than before intervention. These strategies are particularly valuable in urban areas and other landscapes already degraded by human activities. Further studies that highlight significant environmental costs, combined with the documented shortcomings of offset programs, may strengthen arguments for prioritizing tree recruitment and preservation (Gibbons et al., 2010; Kozák et al., 2023; Lindenmayer, 2016).

Enhancing our lifecycle analyses will further support the sustainable supply of hollows. Currently, our calculations rely on input values from literature rather than data specific to our location and manufacturing processes. While this approach enables us to project likely scenarios with confidence ranges that reduce some uncertainty, it primarily serves to demonstrate the potential of this methodology. Accuracy will improve as more detailed information becomes available on manufacturers, energy providers, equipment, and other relevant factors.

Expanding lifecycle studies to include novel materials and methods for calibrating inputs to specific circumstances could significantly advance this work. A practical development would involve integrating the supply and demand of natural and artificial hollows into a unified system. This could build on existing models that simulate staggered recruitment of trees and natural hollows (Gibbons et al., 2010; Holland et al., 2023). Unified models would help identify optimal designs, sizes, materials, lifespans, locations, and quantities of artificial hollows based on the needs of hollow-dependent fauna across different ecosystems.

5.4 | Decommissioning and replacement

A lifecycle approach provides conservation managers with valuable tools to identify effective strategies for sustaining and replacing artificial hollows. Most existing methods overlook the decommissioning and replacement of artificial hollows, yet our findings highlight the importance of assessing hollows over multiple installation cycles for informed design decisions.

Our results challenge the common assumption that longer-lasting hollows always provide the best option. They show that planned decomposition of artificial hollows can reduce waste and pollution. Even with shorter lifespans, using mycelium prototypes instead of plastic at our study site reduces carbon emissions equivalent to what 162 tree seedlings sequester over 10 years and saves the energy consumed by a typical family home for seven years, as estimated by the Greenhouse Gas Equivalencies Calculator (United States Environmental Protection Agency, 2023).

These savings would increase significantly in ecosystems requiring longer timeframes and more hollows. For instance, our scenario includes 1.14 artificial hollows per hectare over 50 years, while other contexts call for 5 to 10 hollows over 140 to 200 years (Lindenmayer et al., 1991; McKenney & Lindenmayer, 1994). These findings highlight the importance of tailoring hollow design and deployment to meet specific ecological and temporal needs.

We recommend that managers use lifecycle assessments to compare a range of artificial hollow designs with varying lifespans, tailored to target species and site-specific characteristics. In most ecosystems, natural hollows take significant time to form, often much longer than the lifespan of a typical artificial hollow (Vesk et al., 2008). Longer-lasting materials may be better suited for species that prefer older hollows created through decay (Ibarra, Novoa, et al., 2020) or for areas unlikely to develop natural hollows in the foreseeable future, such as urban environments or buildings. In contrast, regularly replacing short-lived hollows could benefit wildlife in several ways. Some species, like boreal owls, have higher survival rates in newly formed hollows (Korpimäki & Hakkarainen, 2012). Frequent replacement also reduces parasite build-up and lowers predation risks (Sonerud, 2021). Short-lived hollows offer practical advantages in areas prone to severe events, such as wildfires or storms, where permanent structures might sustain irreparable damage and generate persistent waste. These strategies align with approaches used for other habitat structures. For instance, artificial reefs with changeable modules improve over time through reconfiguration (Suzdaleva & Beznosov, 2021). Temporary shelters made from biodegradable materials like cardboard provide post-bushfire shelter for animals while minimizing waste and avoiding damage to regenerating areas (Hegarty, 2022). In many cases, a mix of hollows with different lifespans works best to preserve forest biodiversity (Cockle et al., 2019; Di Sallo & Cockle, 2022; Wesołowski, 2012). This diversity prevents future shortages (Cockle et al., 2011) and accommodates species with varying habitat preferences (Wiebe et al., 2020).

The challenge lies in achieving the benefits of novel materials like mycelium at affordable costs and with practical manufacturing processes. Our study estimated that selecting the mycelium prototype over plastic would offer significant environmental benefits but cost an additional 15.5%, or nearly €8400 per year. While this cost will likely decrease as production scales and processes improve, it may remain unaffordable in certain contexts. For comparison, this added expense is similar to the cost of installing 20 small nest boxes and supporting volunteers to monitor them for a year (Bainbridge et al., 2018). Future research must confirm these implications in real-world scenarios, as costs vary by location, service providers, installation methods, and maintenance needs. Field tests and additional prototyping will help determine the actual lifespans of prototypes, which differ across ecosystems due to variations in climate, materials, and the behavior of local fauna. Replacement of biodegradable hollows should integrate smoothly into existing management practices without requiring significant additional effort. Managers already perform maintenance every three years (Griffiths, Lentini, et al., 2022; Saunders et al., 2023), conduct annual checks, or relocate hollows every five years (Korpimäki & Hakkarainen, 2012). These examples demonstrate how lifecycle planning supports the inclusion of replacement schedules while addressing sustainability, budget constraints, and resource management.

5.5 | Adaptive management

Our research contributes to the overarching goals of adaptive management by both expanding the scope of options and providing support for decision-making and assessment. Adaptive management is a crucial existing approach in conservation because it acknowledges the inherent uncertainties in managing complex ecosystems. This method emphasizes learning and adapting through iterative decision-making processes, which can lead to more effective and sustainable outcomes (Rist et al., 2013), including approaches that integrate artificial habitat-structures such as tree hollows (Gibbons & Lindenmayer, 2002; Watchorn et al., 2022). The promise of adaptive management lies in its flexibility and responsiveness, allowing managers to adjust strategies based on new information and changing conditions (Månsson et al., 2023). However, implementations of adaptive management can be challenging. It requires significant resources, collaboration among stakeholders, and a robust framework for monitoring and assessment.

Our outline for improved design and management includes the following:

1. Early involvement and framing:
    - Involve designers and engineers early to coordinate information collection and modeling.
    - Frame design challenges and briefs to foster meaningful engagement from stakeholders.
2. Systemic planning and goals:
    - Establish long-term, mid-term, and short-term systemic goals.
    - Analyze patterns of hollow supply, including shapes, materials, methods of formation, and quantities under various dynamic conditions.

- ◦ Forecast hollow supply and replacement needs under different scenarios.
- ◦ Determine the required number of artificial hollows and the duration of commitment needed to maintain supply.

3. Design development and material considerations:
   - ◦ Choose materials and assess lifespans in alignment with site-specific needs, such as target species, recruitment rates, climate, and disturbance risks.
   - ◦ Create bioinformed design options tailored to target species, local structures, and available resources.
   - ◦ Explore a full spectrum of technical and design options to produce innovative and effective designs.
   - ◦ Compare design options based on economics, sustainability, and resilience of hollow supply under disturbances as well as effectiveness in attracting target species.
4. Implementation and monitoring:
   - ◦ Present findings to government, funders, and communities to secure well-targeted investments and long-term commitments.
   - ◦ Install and test different design versions, defined numerically for systematic comparison.
   - ◦ Monitor and maintain installed designs, tracking wildlife response and other management parameters. Share findings with management stakeholders and the community.
   - ◦ Adjust or replace designs as needed, integrating monitoring results and emerging innovations.

This structured approach provides novel opportunities beyond uniform artificial hollows with limited lifespans that do not persist past a single cycle. It promotes innovation, adaptability, and long-term ecological and management success. Potential benefits include:

- Holistic understanding of hollow supply;
- Better integration of natural baselines, shapes, and processes;
- Expanded range of materials, shapes, and techniques for more innovative solutions;
- Better guidance for designers and engineers, leading to more effective scrutiny of designs; and
- Integration of technical iteration and continuous improvement into the management process.

6 | CONCLUSION

This study demonstrates the value of a lifecycle approach in designing and assessing artificial tree hollows, advancing conservation and habitat restoration. By integrating aspects of biological and technological lifecycles to consider long-term environmental and economic impacts, this approach can support the development of sustainable strategies for habitat creation. By numerically modeling the supply of habitat structures over 50 years at a site of more than 650 hectares, our research shows that lifecycle assessments can inform the design, selection, management, and replacement of artificial hollows as interrelated components of an ongoing service. Such analysis is crucial for optimizing the ecological benefits of these structures while minimizing their environmental footprint.

Our findings offer practical insights for a range of stakeholders in wildlife conservation, including managers who work to support hollow-dwelling fauna, funders of initiatives that install artificial hollows, developers that deploy nest boxes in offset programs, and makers of artificial habitat-structures. By detailing the implications of different materials and designs, the lifecycle approach we introduced can aid decision makers in choosing more sustainable options that align with local conservation needs and regulatory frameworks.

Looking forward, it is possible and important to expand our lifecycle analyses to include other ways of providing tree hollows by adding carved logs (Central Coast Council, 2016), drilling holes (Griffiths, Lentini, et al., 2022), inoculating with fungi (Wainhouse & Boddy, 2022), and amending existing cavities (Ellis et al., 2022; Valera et al., 2019). A lifecycle approach can broaden the understanding of environmental impacts associated with such interventions and foster the development of more effective conservation strategies.

The lifecycle-informed designing advocated in this article can have applications in many cases. For example, it is important to assess large-scale deployments of perching sites for birds (Holland et al., 2023), artificial habitat-structures in aquatic ecosystems (Cooke et al., 2023; Lemasson et al., 2024), and bricks for birds and insects (Brighton & Hove City Council, 2020). A lifecycle approach, which views the provision of hollows as an ongoing process, can facilitate better-informed decisions, enhance biodiversity conservation, and address the need for long-term sustainability and resilience in mitigation measures.

AUTHOR CONTRIBUTIONS

Dan Parker: writing—original draft preparation (lead) and review and editing (equal); visualization—images and data presentation (lead); software—computer modeling (lead); methodology—development of methods and creation of models (lead); investigation—performing experiments and collecting data (lead); formal analysis—synthesis of study data (lead); conceptualization—formulation of overarching research goals (supporting).

Stanislav Roudavski: writing—original draft preparation (supporting), review and editing (equal), and abstract translation to Russian (lead); visualization—images and data presentation (supporting); methodology— development of methods and creation of models (supporting); conceptualization—formulation of overarching research goals (lead). **Chiara Bettega**: writing—review and editing (supporting) and abstract translation to Italian (lead); project administration—coordination of the research planning and execution in Italy (lead). **Luigi Marchesi**: writing—review and editing (supporting); project administration—coordination of the research planning and execution in Italy (supporting). **Paolo Pedrini**: writing—review and editing (supporting); project administration—coordination of the research planning and execution in Italy (supporting). **Mattia Brambilla**: writing—review and editing (supporting) and abstract translation to Italian (supporting); project administration—coordination of the research planning and execution in Italy (supporting). **Kylie Soanes**: writing—original draft preparation (supporting) and review and editing (equal); methodology—development of methods and creation of models (supporting); conceptualization—formulation of overarching research goals (supporting).

ACKNOWLEDGMENTS

We acknowledge the traditional custodians of the lands on which we work in Italia and Narrm/Melbourne, Australia. We would like to thank Chiara Fedrigotti, Emilio Coser, Helen Wiesinger, and all the staff at MUSE—Science Museum of Trento for their assistance with this project. We also extend our gratitude to Piergiovanni Partel at the Paneveggio-Pale San Martino Natural Park for his support. We also appreciate the support from all at Deep Design Lab. Open access publishing facilitated by The University of Melbourne, as part of the Wiley - The University of Melbourne agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data for this study are within the paper.

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How to cite this article: Parker, D., Roudavski, S., Bettega, C., Marchesi, L., Pedrini, P., Brambilla, M., & Soanes, K. (2025). Which design is better? A lifecycle approach to the sustainable management of artificial habitat-structures. *Conservation Science and Practice*, *7*(8), e70084. https://doi.org/10.1111/csp2.70084