Journal of Cleaner Production 367 (2022) 133055

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Interactions between buildings, building stakeholders and animals: A scoping review

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ARTICLE INFO

Handling Editor: M.T. Moreira

ABSTRACT

The preservation of biodiversity is a rising global concern and will have a major impact on the design and management of buildings and their immediate surroundings. Thus far, the majority of work on biodiversity and the built environment appears to focus on urban planning, project development, and the niche area of designing buildings with living walls and green roofs. Knowledge on the specific interaction between individual buildings and animals is fragmented, preventing holistic efforts to better manage these interactions. This paper presents the findings from a scoping study which captures the state-of-the-art about relationships between individual buildings, building stakeholders, and animals. It reviews the current body of knowledge and points out three areas of interest that are crucial for future work on this area of study: (1) different stakeholder perspectives of building stakeholders on animals in and around buildings (2) positive and negative interactions between individual buildings and their immediate surroundings with animals and (3) management of interactions between animals in and around buildings. Findings show that literature in relation to these three aspects is fragmented and contains multiple gaps in relation to which species need to be considered and how, including a total absence of mathematical models able to represent animal-building interactions. It calls for better engagement between built environment researchers and their counterparts in biological sciences to collect appropriate data and extract relevant information from it, enhancing knowledge on complex biological processes towards producing shared understanding and developing integrated actions.

1. Introduction

Buildings are omnipresent in human settlements and add a significant contribution to global challenges such as climate change and resource depletion. As a consequence, large efforts have been made on research into building energy efficiency, climate change adaptation of buildings, and the use of sustainably-produced materials in construction. More recently, global concerns about protecting biodiversity and preventing ecocide are increasing rapidly. Biodiversity is now accepted as being of central ecological and societal importance, and it is felt that '*the preservation, conservation and restoration of biodiversity should be a high global priority*' (Timan et al., 2014). The issue features clearly in the United Nations Sustainable Development Goals, with goal number 15 aiming to '*protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*' (United Nations, 2022). Some believe that the effects of biodiversity loss may exceed the effects of climate change (Turner, 2014).

Preservation of biodiversity is a major interdisciplinary challenge, with ecological, socio-economic and management dimensions (Lepczyk et al., 2017). Human activities contribute to the loss of biodiversity by driving habitat loss and degradation, climate change, excessive nutrient loads and pollution, overexploitation, and introduction of invasive species (Winter et al., 2017). Yet, whilst the global decrease in biodiversity is mainly attributed to deforestation, intensive farming and the sealing of green spaces, the role of the built environment remains underestimated (Meier et al., 2020). Within the study of biodiversity at large, the interrelation between the built environment and animals thus far is a research niche at best, primarily because buildings are considered in isolation rather than studied as complex systems inserted in bioregions gravitating around specific natural ecosystems.

So far, the built environment and socio-economic models do not engage with Nature in a sustainable way, undermining its productivity, resilience and adaptability by increasing extinction rates and

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https://doi.org/10.1016/j.jclepro.2022.133055
Received 5 April 2022; Received in revised form 31 May 2022; Accepted 5 July 2022
Available online 7 July 2022

contributing to biodiversity decline, through land use changes and species exploitation (Dasgupta, 2021). These will have catastrophic consequences to our economies, health and well-being and just like mitigating climate change require dedicated actions in each and every building. Addressing biodiversity and animal welfare also calls for action now with respect to multiple elements of the building stock.

Various disciplines relate to biodiversity in the built environment. These overlap and connect but there also may be gaps. Grose (2014) discusses the differences in viewpoints between urban designers and planners and ecologists whereas Dickman (2010) claims that conservation biology is one of the main disciplines that deals with human-wildlife conflict. Further subject areas that relate to animal welfare are biological science, environmental sciences, ecology, urban studies, social sciences and veterinary science (Abusaada and Elshater, 2021). Klem (2015, 2018) points out the role that architects, developers, landscape designers and manufacturers have in the creating buildings that pose a danger to animals, especially birds. Klem (2015) also notes that conservation biologists, legal professionals, and animal welfare scientists/advocates have a role in mitigating and eliminating this danger. In many countries there are laws and regulations to protect wild animals, especially during nesting hibernation and migration. Within development and construction projects, Environmental Impact Assessment (EIA) processes are the general mechanism to assess and manage the presence of animals (Sage et al., 2014). However, typically these laws are in the domain of ecologists and may not be fully considered by architects and urban planners (Meier et al., 2020).

The aim of this article is to review the current state-of-the-art about relationships between individual buildings, their immediate surroundings and animals, and to understand how the literature focuses on this topic from different perspectives, disciplines and knowledge domains. The underlying driver is a quest for actionable information for the architects, engineers and consultants that design buildings. The nature of the research is exploratory, as there is a sparsity of literature that provides a high-level overview of the interaction between buildings and animals in general. Therefore, this is a scoping study that reports on the literature on the subject, exploring the conceptual realm of studies on the interaction of buildings and animals, the pockets of existing knowledge, data availability, and knowledge gaps.

In line with the exploratory nature of the study, literature search terms have been defined on the basis of the keywords present in the research aim: ‘animal’ AND ‘building’ AND ‘stakeholder’, ‘animal’ AND ‘building’ AND ‘interaction’, and finally ‘animal’ AND ‘building’ AND ‘management’. Initial results have been screened for relevance based on article titles, yielding 627 papers. After review of abstracts, 102 papers were selected for further review. Backward search has been used to access 3 seminal papers; forward search could not be used due to the subject having limited visibility. Primarily literature has been searched using Primo (ExLibris), a common front-end discovery service that gives access to all resources available in our institutional libraries. Further dedicated searches were done using Scopus and Web of Science. No limitations were applied to publication dates. The literature search took place between January and March 2022. The analysis of selected papers was based on thematic analysis using a reflective approach.

Findings were grouped according to the following emergent themes:

- The different perspectives of building occupants or stakeholders on *animals in and around buildings.*
- A collection of what is known about *interactions between individual buildings and animals*, predominantly identifying conflicts (negative interaction) and opportunities (positive interaction) in these interactions.
- Reports from the body of knowledge that deals with the *management of animals in and around buildings.*

The paper starts by discussing different building stakeholder perspectives on animals, considering perceptions, attitudes and consequently conflicts that arise from them in the context of the built environment. Perspectives shape interactions between people and animals in the private sphere of buildings and their immediate surroundings and trigger reflections about the role of buildings and their surroundings towards these interactions. Positive and negative interaction between buildings and their immediate surroundings and animals are then mapped and discussed, based on existing literature in this area. The paper finishes with a discussion and conclusions on these findings, highlighting potential avenues for future work.

2. Animals in and around buildings: building stakeholder perspectives and attitudes

Stakeholders’ views about animals in and around buildings are complex and can be basically categorized into different ways according to the following:

- How animals are perceived by the human stakeholders in buildings
- People’s attitudes towards animals in general
- The perceived conflicts animals can cause to different contexts in the built environment and beyond.

2.1. Perceptions

Animals in and around buildings are perceived to interact with humans in different ways; see Table 1. Some animals are considered pests because they are seen to transmit diseases, be a threat to humans and/or ruin buildings and their contents, in which case good practice is to engage in their prevention and control (Lipman and Burt, 2017). Other animals are considered pets and are kept by humans inside their buildings/homes as companions, keeping humans active whilst also bringing other health benefits (Staats et al., 2008) which go from physiological, physiological and social benefits (Ryan and Ziebland, 2015), to benefits related to treating chronic illness (*ibid*) or for the elderly (Enders-Slegers and Hediger, 2019). In addition, there are also liminal animals that are neither pests nor companions but are accepted as living commensally amongst humans (Van Gerwen et al., 2020). See Fig. 1. Other animals fall outside the classification – for instance guide dogs are neither pets nor pest, but also not liminal because they provide a service to their owners (Craigon et al., 2017). There also may be regional differences in perception; for instance in some countries rabbits might be considered an introduced species and pest. Differences in perception are complex and go far beyond these simple classifications. Some people may perceive spiders as liminal, possibly even with some use as they prey on insects. Others have arachnophobia and will classify spiders as pests. Snakes can be considered an even more complex example. Some people have a fear of snakes (as some snakes are

Table 1
Human perspectives of animals.

Human Perspective	References
Animals as pest	Dickman (2010); Gellerstedt (2008); Hickin (1985); Hinkle and Hogsette (2021); Kairo et al. (2018); Ko (2021); Laguna et al. (2022); Lipman and Burt (2017); Maddala (2019); MacFarlane et al., 2007; Morton (2018); Petrovskii et al. (2014); Polak et al. (2020); Querner (2015); Rees, 2003; Sutherst (2014); Wang et al. (2019); Worner and Gevrey (2006)
Animals as liminal species	Abusaada and Elshater, 2021; Van Gerwen et al., 2020; Klem (2015); Klem (2018); Klem (2021); Loss et al. (2015); Machtans et al. (2013); Parkins et al. (2015)
Animals as pets	Enders-Slegers and Hediger (2019); Ryan and Ziebland (2015); Staats et al. (2008)
Other and mixed views	Craigon et al. (2017); Geest et al. (2021); Hurst and Mauron (2009); Liordos et al. (2020); Prokop et al. (2009); Pinillos et al. (2016); Sage et al. (2014); Schoelitsz et al. (2018)

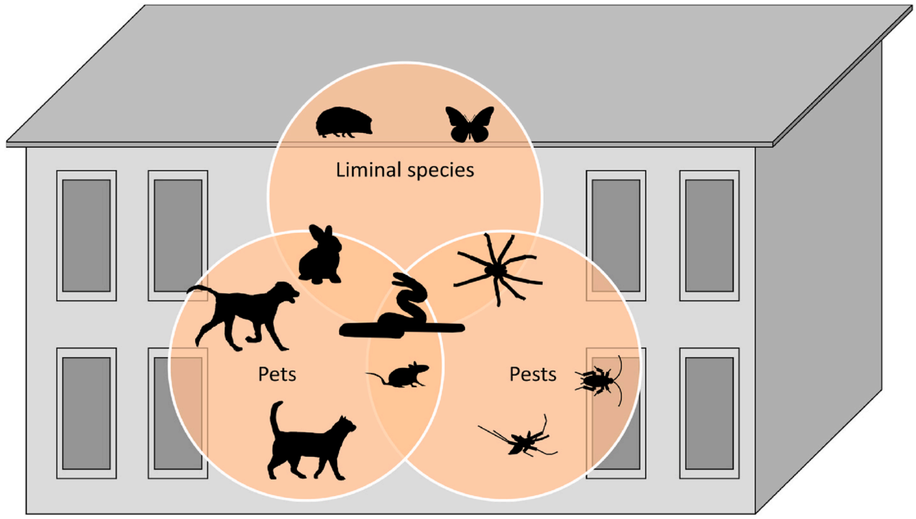

Fig. 1. Different perceptions of animals in and around buildings.

dangerous) and consider them pests, whereas others keep snakes as pets. Yet some use snakes for food or traditional medicine and others will consider them to be a liminal species which is threatened or endangered (Prokop et al., 2009). Beyond that, snakes can be perceived to be useful based on their function in the food chain, or to aid in population control of pest such as small rodents.

Different animal species also capture varying levels of attention and awareness to their existence. Species like hedgehogs, butterflies and honeybees are very much in the public eye and benefit from efforts towards their protection (Liordos et al., 2020; Geest et al., 2021). However, research into spending of people on conservation projects shows a tendency to prioritize animal charisma over endangered status (Colléony et al., 2016). Micro-organisms that live in the soil, inconspicuous beetles and spiders and nocturnal animals are largely ignored by most people, although they may have an important role in the local ecosystem.

2.2. Attitudes

People's attitudes towards animals may be categorized as indifferent, sympathetic but not interested in taking any action on their behalf, sympathetic and willing to help when needed, or generally helpful (Abusaada and Elshater, 2021). Human tolerance levels of natural animals in their homes varies with the animal characteristics, but also relates to the perceived hazard that these animals pose and the information and knowledge that people possess about different species (Schoelitsz et al., 2018). In some cases, attitudes towards animals may be extreme, with people expressing fear, disgust and hate towards some species (Polak et al., 2020; Hinkle and Hogsette, 2021). These may lead humans to opt for pest control, aiming to kill animals using pesticides or other means (Hinkle and Hogsette, 2021).

Attitudes are intrinsically related to human needs which are often described using Maslow's pyramid or hierarchy, which in spite of being over 75 years old, is still a dominant and a well-known theory (Abulof, 2017). The pyramid starts with physiological needs (food, water, shelter that are necessary for survival), followed by safety and security (ensuing health and social stability), before climbing to love and belonging, esteem and respect, and ultimately self-actualization and meaning (Maslow, 1943). Whilst Maslow's theory is explicitly aimed at humans, it is interesting that the lower levels still address the need of the 'organism' and hence will apply to humans and animals alike. Yet animal needs are more typically captured in factors that play a role in animal management, such as the Animal Needs Index (ANI) that is used in farming and which covers practical aspects like freedom of movement, space availability, light regime, hygiene and similar (Herva et al., 2009).

Positive attitudes may lead humans to help, ensuring that wild animals can maintain good health and functioning, preventing that they experience pain and fear, and ultimately allowing them to live lives that are healthy for the species (Abusaada and Elshater, 2021). The crisis related to the loss of biodiversity has shown the need not only to regenerate natural habitats in building surroundings but also demonstrates the benefits this regeneration can have to humans and the built environment as a whole. For instance, the Covid-19 pandemic has augmented human awareness of the crossover of virus from animal to human, which is embedded in a complex context that includes intervention in nature, wildlife trade bans, exploitation of animals for medical testing, and many other factors (Lunstrum et al., 2021). It also caused a significant change in human behaviour through the reduction in activity and mobility imposed by 'lockdowns', which in turn fundamentally changed human-animal interactions and relations (Searle et al., 2021). It is now evident that offering people a connection with nature brings empathy for animals, a sense of oneness, and a sense of responsibility (Cheng and Monroe, 2012). Also known as Biophilia (Wilson, 1984; Kellert and Wilson, 1995), this connection or reconnection with nature, is a psychological orientation which couples experiences of nature with experiences of space and place. Focusing on its wider benefits, primarily related to health and well-being, it has been recently deployed at the building scale and its immediate surroundings via building standards such as WELL (International WELL Buildings Institute, 2022) and Living Building Challenge (Living Future Institute, 2022). However, its implementation and benefits are measured mostly from a human perspective, (e.g., accessibility to nature, percentage of plants indoors, etc.) rather than from an ecosystem perspective.

Research into animal agency, defined as the inner-motivated behavioural engagement of an organism with its environment, animal awareness and animal welfare, and the different levels at which this may be present in specific species needs significant further work (Spinka, 2019). Lack of research in this area leads one to infer that attitudes, and consequently research, about animals are mostly anthropocentric and rooted in the fact that humans assign more value to themselves than to animals (Liebe and Jahnke, 2017). This balance of interests is poignant in the area of animal research (Hurst and Mauron, 2009) and in law where animals are generally considered to be 'things' that are owned by humans. It imposes a clear worldview about which needs should prevail. Yet in the end both animal and human health as well as welfare are interconnected and will benefit from a joined-up approach such as that proposed by OneWelfare (Pinillos et al., 2016).

2.3. Conflicts

Attitudes are also related to potential conflicts which animals can cause to different contexts in the built environment. In the urban environment, meso-animals conflict with humans mostly in relation to health safety and property integrity (Peterson et al., 2010). The basic risks that pest pose to buildings and their occupants are the spread of bacteria, viruses and parasites, allergies and asthma, damage to building structures and fabric, and fire risk due to gnawing of electric cables (Lipman and Burt, 2017). Birds cause a problem due to their droppings, which may damage construction materials, can clog gutters, and will pose health risks to humans in terms of transmission of diseases (Gellerstedt, 2008). People fear that insects may be detrimental to buildings by attracting pests, increasing maintenance and cleaning efforts, doing physical damage, or causing allergies (Meier et al., 2020). Wood boring beetles, moths, booklice, termites and cockroaches pose a substantial risk to historic buildings and their contents (Querner, 2015). House flies have larvae which develop in garbage, carcasses and faeces, and adults are a vector for a wide array of bacteria, fungi and viruses (Hinkle and Hogsette, 2021).

Context is also relevant for how serious a potential conflict might be. For instance, the presence of rats or mice in a hospital is likely to be perceived differently from a similar presence in a private backyard (Van Gerwen et al., 2020). Perception of conflict between animals and buildings, building contents and humans are also dependent on social and cultural factors. Some of these include inequality and perceived imbalance of power, distrust and animosity, vulnerability and wealth, and beliefs and values. Human-wildlife conflicts can also be closely related to human-human conflicts, for instance between authorities and local people (Dickman, 2010). Typical examples are conflicts between local villagers who make a living from agriculture, who are suspicious of wildlife conservation efforts which they feel are driven by either large corporations or urban elites. Such conflicts may lead to disproportionate responses to damage to crops caused by animals.

3. Building-animal interactions

Whilst there is an emerging body of literature on the interaction of the built environment and animals at the larger (urban, district) scale levels (see for instance research in the area of Nature-Based Solutions), less is known about the higher resolution detail that concerns the interaction between individual animals and buildings. One can find studies dedicated to the interaction of specific species with and within the built environment, particularly the brown rat and house mouse (Feng and Himsworth (2013) but a sparsity of information on other rodents' interaction with buildings (Balciauskas and Balciauskiene, 2020). Nasirian and Salehzadeh (2019) review the control of cockroaches in sewers and buildings and Wang et al. (2019) cover both cockroaches and bed bugs. Academic work from the Netherlands notes a scarcity of published work on the prevalence of pests in homes (Lipman and Burt, 2017) whilst others point out that the amounts of animals around buildings varies from location to location, as does the number of species (Ko, 2021), without exploring these variations in more detail.

Table 2 provides a summary of negative and positive interactions between animals and buildings, presented in the left and right columns respectively. The first set of rows in the table represents what buildings might do or provide to animals whereas the second set of rows looks at the reverse and lists what animals may do to buildings. Positive interactions are less frequently reported, despite design projects attempting to explore them potentially through the provision of green roofs and living walls (Mayrand and Clergeau, 2018; Radić et al., 2019).

Table 2
Animals-Building interactions.

Negative interactions	Positive interactions
Building > Animal • Kill/hurt/damage by simply being there (e.g., glass panes: birds) • Disorientation, disturbance (e.g., light pollution) • Scorching (e.g., lamps: insects) • Crush (e.g., windows/doors: insects) • Electrocute (e.g., wires/cables: mammals) • Capture/entangle/starve (e.g., alcoves, basements, service areas: mammals, birds) • Lock animals in ecological traps	• Provide shelter (e.g., sleeping/nesting opportunity: overhangs, crevices, artificial nesting boxes) • Provide new habitats (e.g. green roofs, green facades, etc.)
Animal > Building • Transmission of diseases • Damage to structure & construction (e.g., gnawing, scratching of walls, frames, etc) • Fire risk (e.g., accumulation of nesting material) • Damage to drainage systems • Damage to electrical and control systems (e.g., biting through cables)	• Add ecological value (e.g. integrated design projects)
References Bird window collisions: Gaston et al., 2012; Machtans et al., 2013; Klem 2015; Loss et al., 2015; Parkins et al., 2015; Sabo et al., 2016; Schneider et al., 2017; Klem 2021 Light pollution: Almasi et al., 2015; Gaston et al., 2012; Kyba et al., 2011; Moroni et al., 2017; Pennisi, 2021; Thomas, 1995 Ecological traps: Imlay et al., 2018	Nesting opportunities: Blaha et al., 2019; Meier et al., 2020) Green roofs and living walls: Mayrand and Clergeau (2018); Radić et al. (2019); Strong and Burrows, 2017; Williams et al. (2014); Wooster et al. (2022)

3.1. Negative interactions with buildings

In general, it is believed that '*the vast majority of buildings are still not biodiversity-friendly*' (Meier et al., 2020). Yet Sage et al. (2014) report that '*very little research has addressed the interplay of humans and animals within construction projects*'. Many interactions at this level are not studied or remain unreported such as, for instance, issues related to bird collisions with large buildings and renewable energy systems such as wind turbines (Loss et al. 2015), which except for the U.S. Green Building Council LEED system, fail '*to acknowledge and address the threat windows pose to wild birds*' (Klem, 2015).

The collision of birds with windows/glass results in serious injury and death and could be predicted and prevented by proven measures, for reasons of ethics, animal welfare, and biodiversity (Klem, 2015). The exact number of birds dying from colliding with windows is unknown but there are efforts to estimate this from observational data. For instance, Machtans et al. (2013) estimate that around 25 million birds suffer this fate in Canada each year. They also attribute most (90%) of these deaths to housing due to the dominance of residential buildings in the overall building stock. Loss et al. (2014) estimate a bird mortality attributed to windows in the US at 365 million to 1 billion, with 44% of these deaths occurring at residential homes of 1–3 stories, 56% of deaths occurring at other residential and non-residential buildings of 4–11 stories, and less than 1% of death occurring at high-rise buildings of 12 stories or more. Klem (2015, 2021) estimates the number of bird deaths resulting from crashes in windows at 1 billion or more, with research suggesting that migratory birds are more prone to collision than urban-adapted species (Loss et al., 2015). Transparent glass poses a danger to birds as it presents an invisible, impenetrable barrier (Parkins et al., 2015). Reflective glass is also dangerous as the reflection suggests to birds that there is a habitat beyond them (Sabo et al., 2016). More research is needed to determine the magnitude and reasons behind collisions, such as for instance number of collisions across different building types, geographical and ecological settings, and over time (Loss et al., 2015). More efforts are also needed to correlate collisions to attributes like window area. Schneider et al. (2017) report a correlation with surrounding lawn area and the percentage of land cover with ornamental trees whereas Gaston et al. (2012) correlate collisions of birds with buildings to the amount of light inside indoor environments.

Whilst light pollution is seen as an issue and is covered in building services engineering guides like the Society of Light and Lighting SSL Handbook (Boyce and Raynham, 2009), the impact of this phenomenon on nocturnal animals is mostly ignored. Nocturnal animals often rely on darkness for protection and use the moonlight for orientation and navigation (Kyba et al., 2011). Street lighting can disorient certain species towards finding their natural habitats, for instance, recently hatched baby turtles moving towards cities attracted by streetlights rather than towards the sea. Building lights also contribute to attract species such as moths by confusing their navigation systems, leading them to scorch themselves from hot lights or towards other untimely ends (Pennisi, 2021). Light from buildings can have an important local impact especially when emitted horizontally as nocturnal animals are guided by light from overhead such as moonlight and starlight (Gaston et al., 2012). In addition, artificial light can disturb animal's circadian rhythms and seasonal behaviour, for instance, impacting on the hibernation of bats and amphibians (Thomas, 1995), nocturnal animals like owls (Moroni et al., 2017), or the nesting success of birds (Almasi et al., 2015).

The literature on electrocution of animals is mainly concerned with power lines and ignores building cables and wires potential harm to, for instance, small rodents. Loss et al. (2015) suggest mitigation measures to protect birds from colliding with buildings, such as turning off lights, reducing the number of reflective surfaces, avoiding trapping mechanisms (deep alcoves) and the use of see-trough surfaces, as well as the use of adhesives and stickers as deterring mechanisms. Klem (2021: 56) describes the dangers posed by abandoned buildings that trap American Kestrels on a floor with windows, from which they are unable to escape and where they die from starvation. To quantify the effects of the built environment on animals, Potapov et al. (2014) propose that disturbance may be correlated to a “human activity index”, on a scale from 0 to 10 where zero indicates least impact and 10 maximum impact. However, this is an area that sees little discussion in the architectural and building fields with overall little guidance in preventing buildings from being a danger to animals. Yet, animal suffering and death seems to be accepted as collateral damage.

3.2. Positive interactions with buildings

The positive potential of buildings for animals is discussed in the literature on sustainable and environmentally friendly buildings, especially when green roofs and green facades are considered Wooster et al. (2022) and Strong and Burrows (2017). Findings from Wooster et al. (2022) report that green roofs support many times the number of species than traditional roofs. However, there are concerns about the patch size, quality, abundance and isolation of green walls and systems (Mayrand and Clergeau, 2018) with Williams et al. (2014) suggesting that '*green roof proponents should use restraint in claiming conservation benefits*' and that '*it is premature for policymakers to consider green roofs equivalent to ground-level urban habitats*'.

Efforts are underway to integrate nesting opportunities and shelter in facades (Blaha et al., 2019; Meier et al., 2020). However, some design initiatives, whilst well intended, may backfire. For instance, some buildings may become *ecological traps:* novel habitats that seems more attractive to animals than available habitats, but which in fact reduces their chance of survival or reproduction. An example is a barn with a metal roof, which in Northern American climate conditions is measurably less suitable for nesting by cliff swallows than their natural habitat (Imlay et al., 2018).

Overall, the issue of biodiversity is not yet mainstream in building science. For instance, approaches on how to design for the benefit of animals seems to be missing from the seminal guidebook *Ecohouse* (Roaf et al., 2013). Although real-life projects seem to be attempting to integrate biodiversity more intensively within and with the built environment, adding ecological value to it (Eduard Francois, 2022, Xu et al., 2016; Turenscape, 2022; Hamzah and Yeang, 2022, etc.), interactions between animals and buildings are predominantly perceived as negative and undesirable. This leads to a situation where '*animal interests will almost always be regarded as less important than human interests, even where the human interest at stake is relatively trivial and the animal interest at stake is significant*' (Francione, 2007).

4. Building immediate surroundings and their interactions with animals

Buildings are situated within sites which in ecological terms are ‘ecological patches’. Just as sites are combined into neighbourhoods, districts and cities, ‘ecological patches’ combine into ecosystems which are often best viewed at a neighbourhood or landscape scale (Fletcher and Hotto, 2008). Thus, many buildings, especially homes surrounded by gardens, when grouped together form a significant urban ecosystem that houses animals and provides the context and habitat for human-building-animal interactions. These surroundings have their own direct impact on animals, ranging from building vicinities to wider green areas and green/blue infrastructure at the urban scale. However, from an ecosystem perspective, the built environment landscape is fragmented. It is composed of smaller and isolated habitat patches, affecting animal life, ecological networks, and, in the long-term, overall biodiversity (Ledda et al., 2019).

Table 3 summarises potential interactions between animals and immediate building surroundings, focusing on their private sphere (e.g. gardens, patios, etc.), without upscaling them to the neighbourhood or urban level. As with Table 2, the first set of rows in Table 3 represents what building surroundings might do or provide to animals whereas the second set of rows looks at the reverse and lists what animals may do to building surroundings. Contrarily to Table 2, Table 3 displays more balance between positive and negative interactions showing that there is more knowledge on how to positively interact with animals in buildings' immediate surroundings than on how to positively interact with animals in individual buildings.

Table 3
Animals-building immediate surroundings interactions.

Negative interactions	Positive interactions
Building Surroundings > Animal	
• Habitat fragmentation • Chemicals & pesticides • Increase presence of pets acting like predators (e.g., cats and dogs) • Risks posed by building-related infrastructure (e.g., power lines collisions, traffic, etc.)	• Provide outdoor habitats with food, water and shelter • Provide easy access to food (e.g., fruits, vegetables, feeding stations, etc. in gardens) • Provide natural and man-made shelters and visual cover (e.g., bushes, bird & bat boxes, sheds, etc.)
Animal > Building Surroundings	
• Hygienic concerns • Damage to landscaping • Discomfort/fear	• Add ecological value • Wildlife enjoyment/experience • Natural resistance through exposure • Natural pest control (spider catching flies, mosquitoes)
References	
Urban development and habitat fragmentation: Ledda et al. (2019); Wang et al. (2021) Pesticides: Pekar (2012); Pereira et al. (2021) Pets as predators: Baker et al. (2008); Loss et al. (2015) Traffic risk: Fischer et al., 2017	Use of urban habitat: Murray and St Clair (2017); Meier et al. (2020); Potapov et al. (2014) Wildlife-friendly habitat: Apfelbeck et al. (2020); Anderson et al. (2020); Plummer et al. (2019) Green walls/roofs: Frascaria-Lacoste, 2012

4.1. Negative interactions in the building surrounding private sphere

The conflict between urban expansion and biodiversity loss is an active area of research (Wang et al., 2021). However, details about the role of immediate private building surroundings (gardens, patios, etc.) as animal habitat remains incomplete and is the subject of ongoing research with modern technology potentially playing a key role in gathering more information (Mathieu et al., 2007). This is particularly important because the micro-cosmos that surrounds buildings, with fungi, bacteria and other often-unseen species is especially at risk. These private surroundings are often managed using pesticides and herbicides with knowledge of their impact mostly limited to targeted species rather than their wider effects on other species and the ecosystem (Pereira et al., 2021). For instance, the work by Pekar (2012) points out that most research related to spiders focuses on direct lethal effects of pesticides, with little known about their indirect and long-term effects, via habitat and prey disruption.

In addition to pesticides, pets can be a threat to these fragile ecological patches. For instance, cats roaming in building vicinities may predate on wild birds, small mammals, amphibians and reptiles. Establishing predation rates is a complex research challenge, mostly dependent on partial observation and extrapolation of data with unanswered questions about whether or not predation by cats is compensatory for wild animals who already are in a poor condition, or whether this causes additional mortality (Baker et al., 2008). Loss et al. (2015) explore the death of birds from anthropogenic causes, reviewing cat predation and power line electrocutions as well as bird collision with buildings, automobiles, power lines, communication towers and wind turbines.

However, many species are highly adaptive to urban interventions and environments. Potapov et al. (2014) have explored the habitat use of white-tailed deer in suburbs in the USA, particularly Philadelphia. Murray and St Clair (2017) have studied what attracts urban coyotes to residential yards in Canada and Fischer et al. (2021) have studied the response of swamp wallabies to roads in a human-modified landscape in Australia. Key drivers that attract these animals to urban areas are the availability of food, shelter, and visual cover. Insects and alike, however, remain under-explored (Meier et al., 2020).

4.2. Positive interactions in the building surrounding private sphere

Despite negative interactions listed at the left in Table 3, immediate building surroundings can also positively impact on animals. Interventions such as green roofs and living walls are often seen to provide ecosystems that compensate for loss of nature elsewhere within urban developments. An area that enjoys wide uptake is the growing of pollinator-friendly plants in gardens and parks, in attempt to turn building surroundings into valuable habitats for wildlife (Anderson et al., 2020). Such efforts may be enhanced by the planting of native species which support native wildlife, although utilizing plans from a wider region of origin may have a benefit in that this can extend the flowering season and provide additional resources (Salisbury et al., 2015). Further efforts that support animals in the surroundings of buildings are dedicated design of open spaces and the prioritizing of some areas for animals ('wildlife zoning') through planting of animal-friendly vegetation, especially shrubs and trees, protection of old trees, leaving old and dead wood undisturbed, and the supply of nest boxes (Apfelbeck et al., 2020). Another positive option is the provision of food. For instance, bird-feeding is a common action which in fact supports a multi-billion global industry and which reshapes entire bird communities across large spatial scales (Plummer et al., 2019).

The largest set of positive contributions by buildings come from nature-based solutions implemented at the building level or its vicinities, such as for instance green roofs, green walls, etc. However, these contributions are not based on sustaining or promoting specific ecological habitats but are primarily put in place to provide a service to humans such as improve thermal comfort, reduce urban heat island effects, decrease runoff, etc. The actual contribution of green roofs and walls towards biodiversity is not yet fully clear with concerns that they only have a limited role in terms of connecting natural systems (Henry and Frascaria-Lacoste, 2012). As a result, planners and managers are not instrumented to know what design variables are effective to sustain, attract or repel specific fauna species within urban landscapes, meaning they are unable to prioritize decisions related to the implementation of nature-based solutions accordingly (Garden et al. 2010). Moreover, animals themselves are often not seen as 'stakeholders' who are involved in project development processes, but as passive 'receptors' of such developments (Sage et al., 2014) meaning their potential in providing services to all such as for instance through acting as ecological means to control pests are underexplored, let alone their role in sustaining biodiversity.

4.3. Wider perspectives: species ensembles and ecology

The interaction between animals, buildings and the immediate surroundings of these buildings is part of larger system of interactions and biological chains, which includes populations of animals and plants, the wider community and ecosystem. This is the domain of ecology, which studies the relationships between living organisms and their physical environment (Ghazoul, 2020). In the built environment, ecology typically moves beyond single buildings and their boundaries, focusing instead on the campus, district and urban level; see for instance Barbosa (2020). The word ecology is also used as a broad term to denote sustainable, environmentally-friendly and green buildings; see for instance Graham (2002) on 'Principles for a sustainable built environment' or Berge (2009) on 'Ecology of building materials'. Efforts to apply such principles can be found in for instance work on green business parks (Hwang et al., 2017; Atwa et al., 2019) or green campus initiatives (Ribeiro et al., 2021). Unfortunately, at these higher scale levels and complexity the focus generally moves to good intentions but contains little actionable information about interactions between animals and buildings. There appears to be a disconnect between ecology as understood in the natural sciences and building/urban ecology.

5. Management of animals in and around buildings

Typically, the literature on management of animals in and around buildings focuses on the context of mitigation of human-wildlife conflict. Measures suggested include fencing in and enclosing of areas to ensure physical separation, the use of repellents/deterrents/scaring devices, active guarding, animal habitat manipulation, animal or human behavioural modification, livestock management in order to reduce conflict with wildlife, relocation of people, education and awareness of humans, the creation of buffer zones which act as 'neutral', the provision of alternative food sources, animal population control, and ultimately sterilization and killing of animals. Further interventions are economic and typically involve some form of compensation for damage caused by protected species or involve creating financial benefits from wildlife through tourism (Dickman, 2010).

It must be noted that the behaviour and presence of many species is seasonal with colonies of bees, mosquitoes, termites and others building up in spring (Morton, 2018). Seasonality needs to be factored in the management together with interaction of these animals with other species. Worner and Gevrey (2006) explore the prospect of 'species assemblages' that have co-evolved under certain common conditions and which interact with each other. Therefore, it is not always appropriate to treat species individually; groups of species and their interactions might need to be considered systemically. Systemic management is, however, poorly acknowledged in the literature which is still populated with descriptions of the risks that animals may pose to humans and their assets, such as hygienic concerns (e.g. Farrar et al., 2016), damage to landscaping (e.g. Laguna et al., 2022) fear and discomfort (e.g. Braman and

Griffin, 2022).

5.1. Pest management

The most commonly available set of guidelines on dealing with animals in and around buildings start from the assumption that animals are pest. There is a significant body of literature on pests, and even dedicated peer-reviewed journals such as *Pest Management Science* and the *Journal of Integrated Pest Management*. Pests pose a risk to the health of building occupants via the spread of bacteria, viruses and parasites (Hickin, 1985). They may also cause damage to building structures, fabric and content, and increase fire risks by gnawing in electricity cables (Querner, 2015; Brown and Bostrom, 2005). Extensive knowledge is in place for pests in agriculture, with mathematical and biological models for population control, pest management and extermination. See for instance Petrovskii et al. (2014) on the project of pest population density, or Sutherst (2014) on pest distribution, and Donatelli et al. (2017) on pest life in relation to crop growth. However, there is a lack of knowledge where it comes to transferring these approaches to building-animal interactions (Bleil de Souza and de Wilde, 2019).

Pest control is mostly carried out by professionals, and thus outsourced by building owners/occupants who are mainly interested in identifying where and what the pest is, followed by a way to kill it (Ko, 2021). Killing is often based on the use of chemicals. However, there is pressure to move away from them for being harmful to both the environment in general as well as humans (Rees, 2003), particularly considering this approach can easily get out of control. Pesticides are typically applied with the following methods: spraying for flying insects, surface treatment for crawling insects, fumigation for pests that live inside materials, and baiting for rodents (MacFarlane et al., 2007). For an overview of the current knowledge about the impact of pesticides on human health, see the review paper by Kim et al. (2017). Effects range from short term irritation of skin and eyes, headache and nausea to life-threatening and long-term conditions such as asthma, diabetes and cancer.

Despite little information on systemic management, the literature provides routes to less environmentally harmful interventions focused on prevention and control. Integrated Pest Management (IPM) is a pest control approach that focuses primarily on control rather than killing. It requires proper species identification and monitoring followed by the introduction of preventive measures (cleaning, removing food, closing openings), making use of non-chemical methods to kill animals (mechanical killing traps), with pesticides considered a last resource (Wang et al., 2019; Van Gerwen et al., 2020). Wang et al. (2019) for instance evaluated the effectiveness of IPM in apartment buildings, contrasting this approach to regular pest control treatment and showing significant better results in population reduction. Literature also mentions Green Pest Management (GPM) as a sustainable version of IPM and as something being recognized in green building rating systems (Maddala, 2019). The five stages of GPM include inspection, removal of food and harbourage, exclusion, judicious usage of pesticides, and monitoring (*ibid*). This shift from IPM to GPM already shows signs of recognising the problem of animal/building interaction from a wider perspective, initially filtering negative interactions from positive ones through ecological means to minimize environmental damage to then proceed to the deployment of population control measures rather than blind extermination.

Landscape maintenance in the immediate building surroundings is considered part of pest control. For instance this may include preventing plants from touching buildings so animals cannot climb them towards entry points, selecting plants that do not attract and harbour pests, and taking care that watering does not create an environment that supports pest infestations near buildings (Morton, 2018). In addition, simple devices such as mesh screens can act as animal repellents together with spikes and nets, fogging, sticky paste or liquid together with various other pin and wiring which are particularly good bird repellents (Gellerstedt, 2008). Simple technologies are also reported as efficient against several types of animals, such as self-closing doors or more advanced systems such as fans and air curtains, which are particularly useful in stopping insects from entering buildings (Hinkle and Hogsette, 2021) with Kairo et al. (2018) reporting that an airflow of 7.5 m/s has an anti-insect efficiency of 99.9% $\pm$ 0.2% compared to a situation without an air curtain. Finally, comprehensive passive design measures are provided by (Geiger and Cox, 2012) to control pests in and around buildings (Table 4).

However, the literature is still poor in systemic management, especially in acknowledging that multiple types of species benefit from positive interactions, and even develop adaptations, especially with building immediate surroundings. Thus pest control is far from simple when biodiversity is to be preserved. Systemic management goes beyond a list of positives vs. negative interactions. From an engineering perspective, pest management often requires prediction and simulation in order to assess various interventions. This means that animal behaviour needs to be translated into a complicated set of differential equations which assess population control in relation to different species, fulfilment of multiple ecological functions, and acknowledging that all species are important and have a role to play in guaranteeing a healthy and sustainable equilibrium towards preserving biodiversity.

6. Discussion and conclusions

This paper presents a scoping review of the current literature related to the interactions between buildings, building stakeholders and animals. Whilst the focus is on buildings, the review also includes buildings' immediate surroundings. The building stakeholders' perspectives about animals are important to shape interactions between building and their immediate surroundings and animals and discusses these perspectives together with positive and negative interactions.

The study concludes that stakeholders' perspectives of animals are personal, contextual and depend on their understanding of the importance of the different types of species to the ecosystem. However, these perspectives are primarily anthropocentric and utilitarian considering the way conflicts between people and animals are dealt with, either at the design level or for buildings in use. The literature shows that whilst the built environment destroys and disrupts natural habitats, overall having a negative impact on animals, little is known about which specific building or landscape features should be avoided or promoted to respectively reduce habitat destruction or enable positive interactions with animals to happen.

A review of literature about these interactions reveals a patchwork of knowledge with some significant gaps. On one hand, practical initiatives and literature show clear attempts to promote positive interactions between the built environment and animals, but without clear methods or evidence to achieve them and judge their success. Most of these are in the area of urban design or limited to features such as green walls and green roofs. On the other hand, ecological research on the area of buildings and animals' interaction shows pockets of knowledge or potential biases towards specific classes (birds) and species (rats and mice), rather than any consistent attempts to cover the different ecological

Table 4
Guidelines for designing pests out of buildings (after Geiger and Cox, 2012).

1. Understand local pest pressures (often related to climate)
2. Analyse the physical context of each building (surroundings, vegetation, utilities)
3. Design for necessary pest tolerance (in relation to building function)
4. Use durable pest-resistant materials
5. Design for easy inspection
6. Minimize moisture
7. Seal off openings
8. Eliminate potential shelter
9. Engineer slabs and foundations to minimize pest entry
10. Design buildings to be unattractive to pests (light, vegetation)

niches present in urban environments. Although nature-based solutions attempt to connect and restore fragmented habitat patches in urban environments, there is little evidence that these solutions effectively promote or sustain specific ecological habitats. They are implemented to provide services of different sorts to human building stakeholders with no clear measured benefits in terms of real impact on habitats. This anthropocentric focus aligned with fragmented knowledge affects management decisions about which species to promote and which species to control. It prevents systemic management, i.e., it prevents the assessment of promotion and control as part of a wider effort and stops building actors from playing a key role in the equilibrium of species towards achieving biodiversity.

More research is needed to understand the different ecological niches present in the built environment, so that biological and/or mathematical models can be developed to represent these interactions to properly assess population control towards reaching equilibrium and restoring biodiversity. Plenty of new technologies are now available for these ecological niches to be observed (e.g., digital cameras, electronic tags for tracing, etc.) but little seems to be invested in this understanding, potentially due to the fact it does not bring immediate impact. This lack of knowledge hinders the development of models that represent animal-building interactions. It pushes decision-makers (from designers to pest control agents) to adopt a simplified view with little or no evidence, hindering them to assess design and control measures towards promoting and restoring ecological niches to enhance biodiversity.

Further work is also needed to bridge the divide between the views of ecology in the natural sciences and that in the built environment field. This paper demonstrates that there is knowledge in the natural sciences, for instance within ornithology about the dangers of building windows, that needs to be made accessible to built environment actors.

CRediT authorship contribution statement

Pieter de Wilde: Conceptualization, literature search, thematic analysis, writing. **Clarice Bleil de Souza:** Conceptualization, additional literature search, writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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