

RESEARCH ARTICLE

Open Access



Towards more-than-human heritage: arboreal habitats as a challenge for heritage preservation

Stanislav Roudavski^{1*} and Julian Rutten²

Abstract

Trees belong to humanity's heritage, but they are more than that. Their loss, through catastrophic fires or under business-as-usual, is devastating to many forms of life. Moved by this fact, we begin with an assertion that heritage can have an active role in the design of future places. Written from within the field of architecture, this article focuses on structures that house life. Habitat features of trees and artificial replacement habitats for arboreal wildlife serve as concrete examples. Designs of such habitats need to reflect behaviours, traditions and cultures of birds, bats, and other animals. Our narrative highlights the nonhuman aspect of heritage, seeking to understand how nonhuman stakeholders can act as users and consumers of heritage and not only as its constituents. Our working definition states that more-than-human heritage encompasses tangible and intangible outcomes of historical processes that are of value to human as well as nonhuman stakeholders. From this basis, the article asks how the established notions of heritage can extend to include nonhuman concerns, artefacts, behaviours and cultures. As a possible answer to this question, the hypothesis tested here is that digital information can (1) contribute to the preservation of more-than-human heritage; and (2) illuminate its characteristics for future study and use. This article assesses the potential of three imaging technologies and considers the resulting data within the conceptual framework of more-than-human heritage, illuminating some of its concrete aspects and challenges.

Keywords: Digital heritage, Cultural heritage, Natural heritage, Biological conservation, More-than-human heritage, More-than-human design, Large old trees, Arboreal habitat

Introduction: heritage as a source of knowledge for design

Human impact on the environment is now pervasive and typically damaging. However, even heavily affected places continue to support many forms of nonhuman life (Lowry, Lill, and Wong 2013). In many cases, targeted design can increase such capabilities. One of the author's earlier articles has outlined the notion of more-than-human design that seeks to consider nonhuman stakeholders as equal beneficiaries (Roudavski 2018). Interest in more-than-human design has been growing in parallel with theoretical work that emphasises relational and multi-agential aspects of the world (e.g. see Kirksey 2014). Examples include approaches influenced by continental philosophy,

for example, actor-network theory, posthumanism, trans-humanism, new materialism, object-oriented ontology and other initiatives (e.g. see Forlano 2016 for an overview; Franklin 2017; Maller 2018). In parallel, fields like conservation, restoration and reconciliation ecology (Rosenzweig 2003), including urban ecologies (Douglas and Goode 2011) and ecological engineering (Kangas 2004; Matlock and Morgan 2011) produce evidence-driven work that highlights more-than-human challenges of environmental management and proposes initiatives including rewilding (Owens and Wolch 2019) and cohabitation (Boonman-Berson 2018). Environmental history, biogeography and critical animal geography (Gillespie and Collard 2015), multi-species ethnography (Hamilton and Taylor 2017) and animal studies (Kalof 2017) provide further theoretical background.

Unfortunately, in many cases, the available knowledge on interspecies cohabitation is insufficient. Without such

* Correspondence: stanislav.roudavski@cantab.net

¹Faculty of Architecture, Building and Planning, The University of Melbourne, Melbourne, Australia

Full list of author information is available at the end of the article

knowledge, it is hard to know how to direct design efforts. Natural and cultural heritage protection laws, for example, those defined by the World Heritage Convention, identify places of outstanding value, including old-growth forests, and impose obligations to conserve such places for future generations. Despite these efforts, the degradation continues at an increasing pace. Historical ecosystems and social structures that can serve as useful templates for future places are disappearing. Efforts to safeguard information contained in such systems take many forms. For example, national parks seek to preserve examples of biodiversity *in situ*. In parallel, *ex situ* conservation (Pritchard et al. 2012) includes retention of species in botanical gardens (Krishnan 2016) or genetic information in seed banks (Guerrant, Havens, and Maunder 2004).

Written from within the field of architectural design, this article focuses on the roles of structures that house life. Ecologists call such arrangements habitat structures. A habitat structure is the amount, composition, and three-dimensional distribution of physical matter (both abiotic and biotic) at a specific location (Bell, McCoy, and Mushinsky 1991). Such structures are crucial for the survival of many organisms. Scientists call particularly important arrangements 'keystone structures' (Tews et al. 2004). Large old trees and their habitat features are a characteristic example (Bütler, Rita et al. 2013; Le Roux et al. 2014).

Such trees are rapidly disappearing everywhere (Lindenmayer, Laurance, and Franklin 2012). This article focuses on an Australian case study, but its argument is applicable in many other environments. The global number of trees has fallen by some 46% since the "onset of human civilisation" in the post-Pleistocene period (Crowther et al. 2015, 204). Within Australia, the last two centuries have seen 40% of forests lost to agriculture, logging, urban growth and other human activities (Bradshaw 2012). Within this loss is the global disappearance of large old trees that serve as essential habitats for many species, including birds, bats and insects (Goldingay 2009). It can take hundreds of years before trees form useful habitat features (Lindenmayer et al. 2012). Despite their importance, humans routinely remove large old trees for economic, aesthetic and safety reasons (Le Roux et al. 2014; Conway 2016). Even when humans retain such trees, typical management approaches prescribe elimination of decay, removal of dead or broken branches and filling of hollows, minimising habitat opportunities. Further, typical practices remove dead trees (Carpaneto et al. 2010) even though they can be more valuable as habitats than their living counterparts (Radu 2006). Up to 40% of organisms in forests depend on wounded or decaying material from living, weakened, or dead trees (Bauhus, Baber, and Müller 2018).

The pervasive shortage of large old trees and their ongoing loss necessitate the introduction of artificial alternatives that can include artificial hollows, replacement bark and synthetic trees. Several of our current projects seek to design and test such replacements (Roudavski and Parker 2020). These projects highlight the need for information about successful historical habitat structures. This information is essential not only for the important efforts to conserve the remnant old-growth forests but also for the development of effective artificial replacements of key habitat features in degraded or destroyed ecosystems.

Useful data should describe good homes that have successfully hosted complex lives of many organisms. However, with the disappearance of large old trees, such examples are increasingly hard to find. Predictions suggest that under business-as-usual most Australian large old trees will die within several decades. Extensive areas affected by former or current agricultural activities will experience a total loss (Gibbons et al. 2008) because very few trees started growing and reached maturity since colonisation some 230 years ago. Trees planted now will not naturally form useful cavities for hundreds of years. Even if management practices will adapt to allow trees to mature, age and die in place, researchers and the public will lack useful data on crucially important habitats for many human generations. During this gap, many nonhuman dwellers will perish and others will lose their valuable traditions.

The devastating bushfires of 2019–2020 in Victoria and New South Wales exemplify another form of threat. Early and deliberately conservative estimates by Chris Dickman at the University of Sydney cover the period from September to January. They suggest that in this period the fires have killed over 1 billion mammals, birds, and reptiles in an area exceeding 10 million hectares (Dickman 2020). Unfortunately, the fires are still burning, and the toll will rise. Large old trees, insects, and bacteria will die too. Hundreds of species will go extinct. Countless individuals will become refugees.

In response, this article proposes to extend the concept of heritage to include large old trees, their habitat features and the patterns of life they support. Although existing heritage protections recognise some forests for their outstanding universal value, they do this by assessing their value for humans. We emphasise that large old trees are important to other lifeforms and suggest that practitioners in a range of disciplines should reconsider heritage in more-than-human terms.

Developing this argument, the next section outlines a conceptual framework that builds on the existing work in critical heritage studies and seeks to move beyond natural and cultural distinctions towards more-than-human heritage. After this conceptual sketch, we test

this framework in application to a concrete case-study that considers trees as heritage. The article then reviews the abilities of existing imaging techniques to describe tree habitats and their heritage value. It concludes with an assessment of these techniques and an invitation to share in future work.

Conceptual framework: nonhuman aspects of heritage

Up to this point, the article has discussed trees and their features in terms of data and information, only mentioning heritage as a possible conceptualisation. However, trees are living beings. They exist in complex communities where all stakeholders, living and abiotic, depend on each other. These stakeholders have complex and unique histories that are specific to the circumstances and places within which they have emerged. Data and information are insufficient as tools for capturing such histories. The concept of heritage is more inclusive.

Academic work in heritage studies offers an existing foundation for a more-than-human understanding of heritage. For example, this is one of the key themes in critical heritage studies (Harrison 2013b; Winter 2013). These approaches propose that heritage emerges from relationships between human and non-human actors. This interpretation follows the ideas of the actor-network theory and via this route arrives at the anthropological studies of indigenous worldviews, for example through the work of Deborah Bird Rose and Eduardo Viveiros de Castro.

This basis leads to the interest in non-modern worldviews and ontologies, including, for example, animism and totemism (Byrne and Ween 2015; Harrison 2015). Engagement with these worldviews and the resulting practices can expand the set of imaginable futures and the possible relationships between humans and the rest of the world. Such 'indigenous' or 'traditional' worldviews provide insights and principles that extend beyond universalist, colonising and technocratic approaches. In many cases, they reflect more balanced and sustainable relationships with places than those that are possible through extraction- and growth-driven societies.

Despite their in-depth knowledge of places and their strongly felt kinship with the nonhuman world, indigenous societies' ecological knowledge (Inglis 1993; O'Bryan 2004; Ellen, Parkes, and Bicker 2006; Pierotti 2011; Edington 2017) and the ensuing 'biocultural' approaches to management (Menziez 2006; Sterling et al. 2017; Nelson and Shilling 2018) remain limited by their inescapable human origins. Not all indigenous practices have been sustainable or are scalable. Uncritical privileging of long-lasting human cultures can lead to the valorisation of stable but impoverished places where losses of complexity have likely occurred earlier, during the first wave

of human colonisation (commonly debated examples include the loss of flightless birds in New Zealand or megafauna in Australia). Indigenous knowledge systems also have a limited understanding of many parts of the world that are not accessible via direct experience. For example, the appreciation of the influence of bacteria or solar flares on patterns of life requires technical instrumentation and scientific theories. It might also be difficult to benefit from indigenous ecological knowledge in the existing and emerging conditions where the degradation is severe, as in highly urbanised environments, or where further substantial change is unavoidable, as in places that will be affected by climate change.

An in-depth discussion of these issues is beyond the scope of this article. Instead, our intention is to use the existing discussion on the more-than-human worlds as a basis for future action. One way to proceed is by combining indigenous knowledge (see Latulippe 2015 for an overview) with the latest scientific advances and management practices (e.g. see Kimmerer 2013; Nelson and Shilling 2018; Anderson et al. 2011). The other is by engaging with the notion of indigeneity and constructing procedures that might transition most humans into indigenous relationships with places. Such approaches can be problematic in their underlying drive to instrumentalise and adopt indigenous knowledge into the dominant capitalist and exploitative order (Chandler and Reid 2019).

Moving beyond these approaches, we want to take nonhumans seriously and benefit from the latest knowledge on their capabilities, evolutionary histories, personal biographies and complex needs in the consideration of future planning. Here, the discourse of heritage fuses with the research in cognition, ethology, social behaviour, theoretical biology as well as various forms of ethics, especially those that emphasise ecocentric morals, for example ecocentric ethics (Rolston 2012), geocentric ethics (Lambert 2012) and land ethics (Callicott 2014), astroethics (Impey, Spitz, and Stoeger 2013) animal rights (Donaldson and Kymlicka 2011) and the ethics of care (Puig de la Bellacasa 2017).

The only way to reduce the paternalistic and anthropocentric treatment of nonhumans is by supporting their own voices, rights and freedoms. Among others, this approach has precedents in the efforts to produce history (Gustafsson, Laura and Haapoja, Terike 2015), literature (Brooks 2019), science (Waal 2017) or politics (Wissenburg and Schlosberg 2014) from animals' point of view. However, this important context is beyond the scope here. Nor does this article attempt to develop an exhaustive theoretical treatment of nonhumans within the more-than-human heritage. Instead, our present effort aims to offer a practical and technical example as a provocation for further thinking. However, it is useful to differentiate the proposed approach from many allied

and overlapping efforts to theorise the entangled and heterogenous worlds.

Waterton and Watson (2013) group heritage theories into theories ‘in’, ‘of’ and ‘for’ heritage. The last category of theory ‘for’ heritage is the closest to our discussion because of its emphasis on distributed agency, non-representation and affect. However, this category still emphasises the impact of the multi-agent worlds on humans. The bias towards humans in human discourse is perhaps unavoidable. However, this article seeks to resist it. Here, we propose to focus on the uses or ‘consumption’ of heritage. Existing work on more-than-human aspects of heritage engages with heritage co-constructed with non-humans, living forms of heritage that include active non-humans and forms of heritage that seek to describe or represent nonhumans. In addition, this article proposes that any conception of more-than-human heritage ought to consider ways in which nonhumans can use or consume heritage. This is a difficult challenge, and it is likely that forms of heritage that are meaningful and beneficial for nonhumans can most readily result from human representation. Systems for human representation for legal persons such as rivers provide some workable examples (Youatt 2017). Direct use of heritage by nonhumans might also be possible and requires further consideration.

According to the World Heritage Convention, heritage has both natural and cultural dimensions and consists of natural features, geological and physiographical formations, buildings, monuments and other sites of outstanding universal value. Harrison (2013b, 14) shows that this and other legal instruments separate objects, buildings and landscapes from the ‘everyday’ for the purpose of preserving their aesthetic, historical, scientific, social or recreational values. These elements can retain their meaning with the inclusion of nonhuman concerns.

Nonhuman cultures and cultured nature

The idea of cultural heritage is intrinsically inclusive. Graham, Ashworth, and Turnbridge (2000, 1) suggest that the notion of heritage includes ‘almost any sort of intergenerational exchange or relationship, welcome or not, between societies as well as individuals’. Further, the notion of cultural heritage includes conceptions of and subjective relationships to ‘nature’: nonhuman life and abiotic environments. This is particularly evident in the case of many indigenous cultures.

Current scholarship accepts that heritage does not objectively preserve the past. Instead, the present needs motivate humans who actively create heritage (e.g. see Kirshenblatt-Gimblett 1995; Kuutma 2009). Thus, all forms of heritage are cultural. Contemporary understandings of culture already expand to include nonhuman life and dissociate the notion of culture from the confines of any one species or a set of cognitive abilities (e.g. see Ramsey 2013 for

definitions; Mesoudi 2016 for an overview). Often, cultures of nonhuman species are in a greater need for protection than the organismic carriers of these cultures (Laiolo and Jovani 2007; Brakes et al. 2019; Cordero-Rivera 2017; Caro and Sherman 2012; Whitehead 2010). Furthermore, the present and future needs of humans expressly include beneficial cohabitation with other lifeforms. Consequently, the forms of heritage defined and constructed today should expand to include more-than-human cultures.

Let us now turn to natural heritage. The World Heritage Convention protects natural heritage that comprises natural features such as biological formations. It expects such features to occur within delineated habitats of threatened species. Such understandings characterise heritage as ‘a means by which the quality of life for citizens is enhanced and preserved for future generations.’ This discourse focuses on human interests and is insufficient considering recent work on alternative models of governance that seek to include nonhuman lifeforms as persons (Berg 2007; Shelton 2015) or citizens (Donaldson and Kymlicka 2011). Another limitation is the focus on continuing historical ecosystems rather than on the increasingly common degraded and novel environments. We acknowledge that humans should manage the natural heritage in awareness of impending changes that include large-scale extinctions, continuing urbanisation, climate change and sea-level rises. These conditions invite human and nonhuman cultural considerations into the management of natural heritage and highlight the need to preserve a broad range of traces and expressions, especially where losses have already occurred or are inevitable.

Towards more-than-human heritage

The previous section presented aspects of the expanding notion of heritage in relation to its nonhuman stakeholders. This section builds on these components to propose a working definition of heritage that can encompass human and nonhuman concerns. Precedents to more-than-human heritage include the notion of relational archaeology (Watts 2013), the archaeology of animals (Hill 2013; Mitchell 2018; Boyd 2017) and the proposal to preserve nonhuman tangible heritage (Spennemann 2007). As discussed above, the proposed definition builds on the existing conceptualisations that emphasise more-than-human worlds and their relevance for heritage in the future (DeSilvey and Harrison 2019). A complete definition of more-than-human heritage will be premature without further theoretical development, but our working definition is as follows: more-than-human heritage encompasses tangible and intangible outcomes of historical processes that are of value to human as well as nonhuman stakeholders.

From this basis, this article asks how the established notions of heritage can encompass nonhuman concerns, artefacts, behaviours and cultures? We hypothesise that digital information can (1) contribute to preservation of more-than-human heritage and (2) illuminate its characteristics for future study and use.

The next section tests the proposed framework of more-than-human heritage by applying it to a concrete example.

Case study: trees as an example of heritage

This example, borrowed from our existing projects that focus on the provision of artificially constructed habitats (Roudavski and Parker 2020), is a tree. Plants have many aspects that can be relevant as heritage, which can be evident from examples of human approaches to knowing trees.

(Thomas [2000] 2014, 1) observes that for biologists a tree is any plant with a self-supporting perennial woody stem while for horticulturalists, a tree is a plant with a single stem of more than 6 m in length, which branches at some distance above ground. Within ecology, a tree is a competitor whose canopy shadows other plants (Begon, Townsend, and Harper [1986] 2006, 129). Agroforestry sees trees as ‘forest products’ which humans can convert into ‘industrial raw materials’ (Shmulsky and Jones [1982] 2011).

Attempts at formal descriptions or measurement also diverge (Morris 2018). For example, L-systems represent trees in terms of length and angles of branches in recursive patterns (Prusinkiewicz et al. 2018). Alternatively, laws of physics can predict plant stress, strain, wind drag and photosynthesis in approaches similar to engineering (Niklas and Spatz 2012). However, the parallel to engineering can be misleading. For example, the conventional distinction between structure and materials that applies to buildings or furniture breaks down with living plants. Further, relationships between form and function in organisms cannot be known a priori and always remain speculative (Bock and von Wahlert 1965; Gould and Vrba 1982; Amundson and Lauder 1994). At the scale of forests, trees become dissipative systems that gather, store and apply solar energy (Maser, Claridge, and Trappe 2008, 111).

This partial list of different understandings and representations of trees illustrates the difficulty of conceptualising them as objects of preservation and heritage. To approach this task, the next section gathers valuable features of trees as lists, focusing on their characteristics as habitats for other lifeforms. Harrison (2013a) points out that the compilation of lists is one of the primary practices within professional heritage institutions. These lists authorise some entities as heritage in preference to others but cannot capture the complex uses and meanings of heritage for its consumers. They also tend to retain all listed objects irrespective of their usefulness to

heritage stakeholders and lack the tools for forgetting entities that lost their value (Harrison 2013a). These problems will only increase if the range of heritage stakeholders (users and consumers) expands to include nonhumans. The issues of managing more-than-human heritage in reference to more-than-human cultures will require further research. The discussion below takes the first steps in that direction by discussing trees from the viewpoints of arboreal wildlife. For birds, bats and insects, trees can function as equivalents of cultural landscapes, with all the ensuing complexities of communal dwelling, interpretation and memory.

Trees as habitats

Large old trees play many roles within their ecosystems (Lindenmayer and Laurance 2016). This article focuses on one of these roles and considers trees as homes to other lifeforms. For convenience, this section groups habitat features into landscape, structure and food. These lists borrow from a variety of sources on ecology, conservation and natural heritage (Bütler, Rita et al. 2013; Lindenmayer and Laurance 2016; Colloff 2014). All these characteristics require further ecological research, are important for many lifeforms, and are under various degrees of threat (Fig. 1).

Landscape

Each tree exists in an extended environment, and its analysis as a habitat or potential heritage can begin at the landscape or even biome scales. Local bush and forest communities are also important. However, for brevity, this article focuses on the examples from the narrow range as discussed below:

- (a) Under the ground. Roots of trees regulate the habitat below the ground. For example, deep taproots of large trees draw up nutrients and water. This action contributes to the beneficial habitat characteristics for smaller trees, shrubs and herbs. Many human activities undermine such habitats. Examples include altered water regimes, over-fertilisation and grounds covered with mono-crops (Fig. 2: left and middle) or artificial sealants (Fig. 2: right). These complex interactions between biotic and abiotic elements reflect the subjective capabilities of living stakeholders and are unique to places and cultures. Technical approaches of agriculture cannot reproduce them on demand. Human cultures have registered the value of such phenomena as terroir (Trubek 2008) and petrichor (Wright 2017, 147), most frequently with economic profit in mind.
- (b) On the ground. Surrounding the tree on the ground is coarse woody debris and leaf litter. These objects (Fig. 1 and Fig. 3: bottom left) provide shelter and

food sources for small animals including invertebrates, mammals, marsupials and birds as well as for plants, fungi and lichens. These lifeforms aggregate into complex ecosystems that can take hundreds or even millions (Mitton and Grant 1996) of years to form. Old habitats of this type are rare because humans routinely remove debris for access or to comply with perceived safety, hygiene or aesthetics. These aggregations enable and express local knowledge and traditions of practical use as well as aesthetic preferences of many lifeforms.

- (c) Above the ground. Canopies provide shading and act as windbreaks, sheltering aerial habitats from harsh environmental conditions. Neighbouring trees create habitats for each other. For example, trees can resist wind or insect attacks better when growing in a group. Plant communication (fungal hyphae), pollination (insects) and seed dispersal (birds and others) often depend on mutualistic relationships with other lifeforms. Coevolution of organisms, subjectivities and behaviours is the context that frames the communities and cultures within old-growth forests. Without this interspecies cultural history, many features and capabilities of

individual organisms lose their meaning, leading to impoverishment and possible suffering. When humans remove trees and tree limbs within urban environments, they create sparser environments (Fig. 2 and Fig. 4) where trees cannot form communities and lack many useful habitat features. Rich interactions in tree communities deserve attention and preservation as a form of heritage (Fig. 2).

Structure

Beyond contextual features, important elements of preservation, especially in the context of this article's focus on habitat, are characteristics of tree geometry.

A tree's architecture is an arrangement of its parts at a given time. This arrangement expresses the state of interactions between plant growth and environmental conditions (Barthélémy and Caraglio 2007). All ecosystems transition through semi-stable states (Maser, Claridge, and Trappe 2008), mostly gradually but sometimes abruptly. Consequently, tree architecture reflects intrinsic patterns of growth combined with external impacts such as fires, insect outbreaks, fungal attacks and weather events. Such impacts lead to injuries, for example, broken branches or damaged bark. Injuries start processes of decay that result in habitable hollows (Lindenmayer 2009). Trees interact



Fig. 1 A large old tree (river red gum, *Eucalyptus camaldulensis*) and its habitat features. Top: canopy branches, deadwood, leaves, seeds and flowers. Middle: broken branches, hollows, rough bark and trunk fissures. Bottom: fallen leaves, bark, and branches (Source: Chris Tangey)



Fig. 2 Tree context. Left: a river red gum (*Eucalyptus camaldulensis*) within managed agricultural land. Middle: a river red gum in an urban park. Right: a river red gum among paved surfaces (Source: the authors)

with the surrounding lifeforms such as birds and bats that nest within cavities or insects that eat the foliage and burrow into the bark. Animals select hollows based on characteristics such as shape, orientation, entrance size and height from the ground (Le Roux et al. 2016). The resulting tree's geometry is a product of coevolution and complex historical relationships. It is distinctive in multiple ways, for example at genotype (or species) and phenotype (or individual) levels. Individual trees have unique life histories that are specific to the places they inhabit. Multi-species communities and individuals living in such places impact on tree biographies. In turn, trees affect all local life and abiotic conditions. Metabolic as well as cultural interactions of local lifeforms aggregate into distinct patterns that can be many thousands of years old, complex, rich, large or rare.

Here, we list some key features of a tree's geometry in relationship to characteristic behaviours of other lifeforms:

- (a) The bark, hanging, loose, and with deep fissures, creates a variety of microhabitats for invertebrates (Fig. 1 and Fig. 3: top right).
- (b) The branches provide perching sites for nesting birds and substrates for lichens, mosses and other bryophytes.
- (c) Deadwood in the canopy offers roosting sites that are important for hunting and social activities (Fig. 1 and Fig. 3: top left).
- (d) Buttresses at the base of trees are another site for bryophytes, (Fig. 3: bottom right).
- (e) Exposed roots attract and protect fish when submerged and allow nesting opportunities for birds when exposed (Fig. 3: bottom middle).
- (f) Hollows are a crucial habitat feature of large old trees (Fig. 1, Fig. 4, Fig. 5, and Fig. 8). A wide variety of

vertebrate and invertebrate species depend on hollows for their survival (Fig. 3 and Fig. 4).

Human dwellers can love their homes, defend them against intruders and feel lost and nostalgic when away. Animal dwellers possess parallel capabilities. They can know their home environments in detail, exhibit powerful site attachment, can defend their territory and teach their young about the place features and traditions. When humans forcibly relocate animals to make room for infrastructure projects, they become refugees in their new places, not welcomed by the local populations, deprived of their place-specific traditions and depressed. Their places (Hadley 2017), objects and expressions are plausible items of protection and heritage.

Food

The concept of heritage readily includes human food traditions (Timothy 2016; Brulotte and Di Giovine 2014). Animals and other organisms also enjoy food. Nonhuman diets can change under pressure, for example, in proximity to cities or in adverse climatic conditions. Sometimes, these beneficial dietary traditions disappear and new habits can be detrimental to health and wellbeing. Thus, nonhuman food and the associated phenomena can also fit into the notion of more-than-human heritage.

Trees provide a variety of nutrients. Plants' ability to convert solar energy into nourishment for other organisms is fundamental to a vast majority of ecosystems (Ripple et al. 2016). However, human modifications of landscapes (Fig. 2) disrupt such flows of energy. Trees' contributions to nourishment change through their life histories, becoming more diverse with age and continuing after their deaths (Stokland, Siitonen, and Jonsson 2012). Records of the spatial and temporal distribution of



Fig. 3 Tree habitats. Examples of a range of supported by within river red gums. Top left: deadwood in the canopy. Top middle: damaged sapwood. Top right: rough bark. Bottom left: fallen limbs, bark and leaves in the understory (image by Kate Bennetts) Bottom middle: exposed roots. (image by Michelle Ridgeway) Bottom right: root buttresses (Source of all inattributed images: the authors)

nutrients can further the understanding of ecological functions of trees, support their long-term management and inform designs of artificial replacements, where necessary. A selection of relevant tree features includes:

- (a) Flowers, seeds and fruits are food resources for animals, fungi, and invertebrates. When trees bloom, they attract a wide variety of pollinating animals, including bees and bats. These seasonal feeding activities are vital indicators of ecosystem health, and we interpret them as a form of intangible heritage.
- (b) The sapwood within the bark is a nutrient for wood-boring invertebrates (Fig. 3: top middle). In turn, invertebrates are a valuable food source for predatory species. Human management of trees undermines such long-lasting relationships. Recording of these complex habitats as heritage can leave a record of their structure and functionality.
- (c) The roots of trees form symbiotic relationships with mycelium and neighbouring plants. Such networks transfer nutrients and water that are vital to many tree communities. Human modification of such ecosystems and global transportation of soil destroy these subterranean communications. Old examples

of underground nutrient systems might be another target for heritage preservation.

Trees and heritage preservation

This section gives brief examples of trees as tangible and intangible heritage. It points out some existing techniques for the preservation of these types of heritage and highlights how nonhumans can use heritage indirectly via design. The challenges outlined in this section provide targets for the imaging techniques discussed below.

Trees as tangible heritage

We use hollows as a concrete example to zoom into tangible aspects of trees as heritage. Hollows provide a concrete, practical challenge for heritage preservation. Their geometric features reflect complex life histories. Animal, wind, and lightning-strikes damage stems and branches that then become hosts to many interacting organisms including insects, fungi and bacteria. As a result, woody organs hollow out (Fig. 4 left and middle) (Wilkes 1982; Gibbons and Lindenmayer 2002; Wormington et al. 2003). Human modification of broken limbs aims to protect trees from further damage, with clean cuts and protective treatment of the damaged sites (Fig. 4: right).



Fig. 4 A tree hollow's life history. Alternative histories of broken branches of river red gums. Left: initial state, a decaying branch. Middle: outcome one, after fungal and animal modification. Right: outcome two, with human modification (Source: the authors)

Such operations stop the formation of hollows, reducing their ecological benefits. Large old trees that have developed such cavities are crucially important because they provide valuable habitat features (Manning et al. 2012). Goldingay (2009) estimates that globally some 500 species of bats and 260 species of birds rely on tree cavities. Size and geometry of hollows (Fig. 5) determine who and how can occupy them, as listed below:

- (a) Small cavities appear when animals excavate hollows (Fig. 5: top left). On the top sides of branches they fill with water and provide breeding sites for invertebrates and frogs.
- (b) Broken branches hollow with fungal and animal modification and offer sites for nesting, roosting and denning (Fig. 5: top middle, top right, bottom left).
- (c) Dead trees hollow out with large cavities and multiple entrances offering habitats for many animals (Fig. 5: bottom right).
- (d) Cracks and fissures develop into larger cavities that support invertebrates (Fig. 5: bottom left). Fire can enlarge an ageing tree's cavities and create roosting sites for bats, (Fig. 5: bottom middle).

Current silviculture and heritage practices do value and preserve trees. A common approach is first to increase the longevity of a tree and then, at the end of its life, to replace it with a genetically or functionally similar specimen. In Australia, many municipal or corporate 'tree management plans' specify such tree retention and replacement strategy (e.g. see Chen 2005, 161). Despite such regulatory constraints, economic and safety priorities often lead to the removal of significant trees. When this occurs, current preservation approaches might arrange to capture tangible aspects of trees in the form of images (e.g. see State of Victoria 2019, 48). However, such records are not adequate for the preservation of more-

than-human heritage features. A loss of a large old tree is likely to kill or disadvantage many organisms. Images and oral records cannot capture the complexity of tree geometries or surrounding life patterns. Nor can a new and young tree provide an adequate replacement (Fig. 5).

Trees as intangible heritage

Trees already play a part in intangible heritage. For example, humans value archetypal trees as gifts from God, emblems of the righteous (Musselman 2003; Norkunas 2017) or symbols of ancestral lands (Keller 2008). Living trees also can have symbolic value as witnesses of cultural practices (Farmer 2019; Porter 2006). Digital imaging techniques can be useful in these cases because trees die, decay and disappear. When they perish, memories of their importance fade, too (Cloke and Pawson 2008; Farmer 2019).

The high-fidelity imaging of trees becomes even more important in application to more-than-human heritage. The discussion above indicated that trees serve as sites for complex behaviours, traditions and cultures that involve human and nonhuman stakeholders. Trees and other organisms can form a range of relationships from tightly symbiotic to culturally opportunistic. Preservation of such arrangements as memorials or as templates for future study and action is important for a variety of reasons. However, narrative and metaphoric forms of preservation that might work for the intangible heritage of humans are insufficient in this case. For example, current practices might suggest capturing cultural aspects of trees as oral stories (e.g. see State of Victoria 2019, 48, as above). However, oral records cannot account for the complexity or dynamism of more-than-human interactions, particularly because such interactions are often hidden and incompletely understood.



Fig. 5 Hollows in large old river red gums. Top left: a small cavity. Top middle: hollow from a lightning strike. Top right: a large hollow from fallen branches (image by Colin Judkins). Bottom left: a large fissure and a protruding hollow. Bottom middle: a root cavity enlarged by fire (image by Friends of the Albury Botanic Gardens). Bottom right: a snag with a large hollow and numerous entrances (image by Colin Judkins) (Source of all inattributed images: the authors)

Trees as heritage in design

The disappearance of large old trees motivates the efforts to replace hollows, bark, and whole trees with artificial structures (Hannan et al. 2019). An illustrative example of this approach is the design of prosthetic hollows for a powerful owl, *Ninox strenua* (Roudavski and Parker 2020). Nesting owls use large hollows, high off the ground, and in proximity to food and flowing water (McNabb 1996). The supply of natural hollows is diminishing, and almost none exist in inner cities (Isaac et al. 2014). Information documenting successful hollows and their surrounds could significantly aid the design of replacements. Our approach to the design of artificial habitats uses automated digital-design techniques to generate form. The use of such techniques allows the resultant structures to match the geometries of host trees and replicate key characteristics of precedent hollows (Fig. 6: right). Our current work uses three-dimensional imaging, specifically light detection and ranging to capture the data describing such precedents (Fig. 6: left and middle).

This example highlights several valuable uses of digital imaging data within future-oriented, more-than-human heritage: (1) for the preservation of valuable features that are likely to disappear, such as large old trees; (2) for collection of comprehensive datasets that might preserve

valuable entities for the use by future generations that might ask questions and deploy the techniques that are not currently available; (3) for documentation of change in the environment that is otherwise imperceptible or not measurable; and (4) for computational simulations that can explore ecosystem interaction in changing conditions (Fig. 6).

A broad range of other design and management-related uses for more-than-human heritage can prove useful in the future but this discussion is outside of the scope of this article. Most commonly, nonhumans will encounter heritage in the field, through their living bodies. They can visit heritage items (such as preserved or artificial nests), contribute to the understanding of heritage (by using it in the presence of others) and engage in conversations about heritage (by modifying their behaviour in response to heritage interpretations). Perhaps in the future, with support and under case-specific limitations, nonhuman lifeforms can also assume roles of 'heritage citizens' (Lewi et al. 2016).

Technique assessment: capturing and preserving trees as heritage

Three-dimensional imaging techniques are now common in artefact description, analysis and heritage preservation.



Fig. 6 Representations of hollows. Left: light detection and ranging scan of a large tree and its context. Middle: light detection and ranging scan of a hollow. Right: physical prototype of a prosthetic hollow by Dan Parker (Source: Roudavski and Parker 2020)

This article focuses on three techniques: photogrammetry (passive), laser scanning (active) and computed tomography (active). Comparisons of such techniques already exist (Remondino 2011) and multiple techniques in combination often produce better outcomes (Ramos and Remondino 2015). This article follows this comparative work and aims to sample common and relatively accessible techniques in application to some characteristic challenges of more-than-human heritage as described above.

Technique descriptions

Surface imaging

Photogrammetry is a technique that infers three-dimensional qualities from two-dimensional images (Wolf, Dewitt, and Wilkinson [2000] 2014). This article evaluates two such techniques, stereophotogrammetry and structured light photogrammetry.

Stereophotogrammetry is a technique that uses a camera to generate two-dimensional images of the scanned object. An algorithm uses relative displacements of similar features within two or more images to generate a three-dimensional surface (Fig. 7: middle). The use of images allows the resultant model to have a photorealistic surface (Fig. 7: left bottom).

Structured light photogrammetry is a method that projects a calibrated pattern of light onto an object (Luhmann et al. 2011). The software uses the distortion of this pattern to construct a three-dimensional surface (Fig. 8: right and left bottom).

Devices that use photogrammetry method range from personal cameras to specialised equipment. Such equipment is typically small and portable. The fidelity of the outcome relies on image resolution. In general, photogrammetry techniques are easy to use. The well-automated software produces a completed model in less than a day.

Light detection and ranging techniques (Luhmann et al. 2011) emit a single pulse of light and capture the time and intensity of the returned light. The scanner scatters this light in a spherical pattern and measures angles and distances from the projected points to the emission origin. Post-processing software combines information from a 360-degree image and the points from the laser scan to assign each point a colour value (Fig. 6: left and middle and Fig. 7: right).

Light detection and ranging techniques require devices that range from stationary to mobile and terrestrial to aerial. Large areas and complex objects require multiple scans increasing the number of points and the size of the resultant data. The user usually needs to use specialised software to align and merge multiple scans. This reduces reliability, increases processing time and produces large files.

Volume imaging

Computed tomography transmits X-rays through an object and captures the variation in radiation (Hsieh [2003] 2009). The apparatus records the radiation at a variety of angles, calculates a 3D grid of intensities and saves them as a stack of images that slice the target object (Fig. 8: middle). Within computed tomography is microscopic computed tomography. This technology produces finer sub-millimetre resolutions. This, however, limits the maximum scannable dimensions (Holdsworth and Thornton 2002).

Computed tomography devices work in laboratories, with rare exceptions. Typical maximum scannable volumes exceed the dimensions of a human body. They require a technician to operate and process the raw data. The ensuing volumes of data are significantly larger than those produced by surface scanning techniques resulting in greater scanning and processing times (Fig. 7 and Fig. 8).

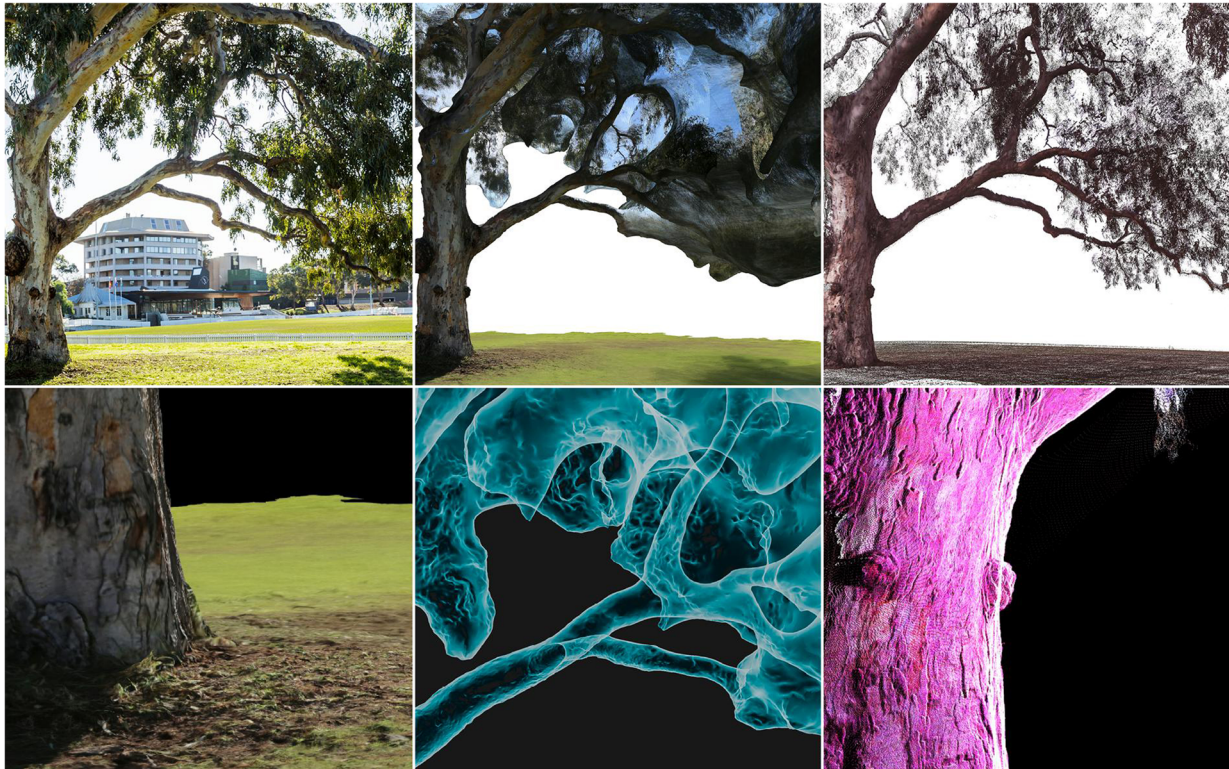


Fig. 7 A remnant river red gum captured by photography, photogrammetry and LiDAR. Top left: photograph. Top middle: photogrammetry. Top right: LiDAR. Bottom left: detail of the photogrammetry texture. Bottom middle: detail of the photogrammetry mesh. Bottom right: detail of the lidar points (Source: the authors)

Technique analysis

This section consists of two parts. First, it briefly outlines the interaction between target entities and the imaging equipment, highlighting characteristic challenges that emerged during testing. Second, it illustrates the application of imaging to one type of entity—tree hollows—in more detail.

Outline: targets, equipment and issues

The following is a list of typical issues that result from imaging trees:

Visibility. Issues of visibility include occlusion of target objects by other entities as well as self-occlusion of overlapping branches or peeling bark. Another type of visibility constraints pertains to the size of the target objects. Imaging devices can operate within set ranges that might not fit tight spaces or reach far enough to capture the whole entity. Surface imaging from multiple angles can overcome occlusion but only partially. Volume imaging techniques do not suffer from occlusion but might not register all materials within an entity.

Positioning. Issues of accessibility constrain the placement of equipment in relation to target entities. For example, tree cavities can be too small, root

systems can be invisible under the ground and sapwood covered by tree bark.

Resolution. All techniques output data at limited resolutions. A compromise that balances the size of an entity, the number of captures, the processing time and the data density is typically necessary. The scale of tree-habitat features can vary widely, from bark crevices to groups of trees.

Repeatability. Trees have unique life histories. They grow and suffer environmental impacts. These multi-speed dynamics are important characteristics of their habitat features. Repeated and comparable imagining is necessary to record such events, resulting in difficult tasks of calibration and data comparison, among others.

Interpretation. All imaging techniques require further processing to isolate or distinguish relevant features such as trunks, leaves, dead or living branches, hollows, etc. Some of these features, such as flowers, can vary greatly in size and abundance, between species of trees, their sexes and over time. Manual interpretation is very slow and subjective. Automated techniques, including those of artificial intelligence will be necessary to process realistic volumes of data.

Accessibility. Accessibility refers to the ease with which an operator can deploy a technique in the field. Aspects



Fig. 8 Hollows and bark. Top: samples. Bottom: imaging outputs. Left: yellow box (*Eucalyptus melliodora*) tree hollow imaged with structured light photogrammetry. Middle: the internal surface of a hollow imaged with computed tomography. Right: rough bark of a yellow box imaged with structured light photogrammetry (Source: the authors)

of this category include costs, the need for expert knowledge and experience, time to set up, the need for specialist transport or auxiliary equipment, tolerance of equipment to field conditions, etc.

Example: imaging tree hollows

Hollows are a characteristically difficult challenge for imaging.

Habitat hollows are meaningful within their contexts. Locations of hollowed trees within their surroundings, positioning of hollows in tree organs, entrance geometries and configurations of neighbouring branches all influence hollows' habitat affordances. Given this, size, accessibility, and visibility emerge as significant constraints on imaging. Light detection and ranging techniques can capture surrounding branches and entrance geometry (Fig. 7: top right). During these imaging tasks, occlusion is common. A combination of aerial and terrestrial imaging can partly overcome visibility issues (Roşca et al. 2018). However, photogrammetry from greater distances cannot differentiate geometry sufficiently (Fig. 7: top middle). The utilisation of drones might provide additional vantage points, but piloting them through complex tree crowns can be challenging or impossible. Volume imaging techniques are not applicable at required scales.

Externally, bark or other similar surfaces cover tree organs that contain hollows. Such surfaces can be highly detailed or porous. Stereophotogrammetry cannot capture such complexity but provides high levels of visual detail in favourable spatial positions (Fig. 7: bottom left and middle). When imaging close to the object, structured light photogrammetry (Fig. 8: right) as well as light detection and ranging (Fig. 6: middle and Fig. 7: right) capture high levels of detail. However, they have limited capabilities to overcome frequent self-occlusions. Computed tomography can capture the highest level of volumetric detail (Fig. 8: bottom middle). However, tomography cannot capture colour information and standard tomographic equipment cannot operate in the field or capture living trees *in toto* or *in situ*.

Internally, hollow shapes, textures, and debris are important characteristics. Complex detailing poses challenges that are like those encountered during external imaging. In addition, spatial confinement of hollows provides a further constraint to surface imaging techniques because most devices cannot fit into tree hollows or operate at such close distances (Fig. 8: left). The development of new devices or redeployment of existing techniques used for bore-hole scanning or dental imaging might provide additional possibilities.

Structurally, properties of hollows, such as strength or insulation, depend on wall thicknesses, densities, grains and other characteristics. Because of the confinement constraints, only volume imaging techniques can capture such characteristics. The outcomes of computed tomography can distinguish internal cavities and changes in density (Fig. 8: bottom middle), however, this technique cannot isolate water content. Other volume imaging techniques such as magnetic resonance imaging can capture water. However, such techniques would require living or recently removed samples examined *in pars* and *ex situ*, posing further restrictions.

As mentioned above, imaging of hollows can happen *in situ* or *ex situ* and *in toto* or *in pars*. There are two benefits for *in situ* imaging: (1) prevention of damage to living trees and their neighbourhood, and (2) ability to capture contextual information. With the removal of the hollowed part from the tree, an *ex situ* approach allows for more flexible preservation and imaging techniques including multiple imaging sessions, controlled conditions and an opportunity to complement imaging with other approaches such as casting. In principle, imaging *in toto* provides the most coherent and continuous data. However, such imaging is rarely possible with available technologies. Imaging *in pars* allows the repeated application of machines with limited ranges but requires systematic methodologies and specialist skills. Anatomical studies of other organisms provide precedents for dissections varying in relationship to intended uses.

In general, existing and currently imaginable techniques are insufficient to cope the full complexity of tree habitats. These limitations emphasise the importance of maintaining and regenerating living ecosystems and cultural landscapes. At the same time, our experiments show that digital imaging can be useful to preserve some aspects of trees.

Conclusion: more-than-human heritage and design

This article hypothesised that digital information can (1) contribute to the preservation of more-than-human heritage and (2) illuminate its characteristics for future study and use.

To test his hypothesis, this article first emphasised the nonhuman aspects of the more-than-human heritage, then considered habitats provided by large old trees as a concrete test-case for such heritage, and finally assessed the capabilities of digital-imaging technologies to preserve its sample features.

We began by suggesting that heritage can have an active and future-oriented role in the growing field of more-than-human design. Access to documented histories, behaviours and artefacts is essential when the clients of design are nonhuman; that is, when design aims to create habitats that can support the lives of all organisms.

The next stage of the argument sought to extend the existing research on more-than-human worlds by emphasising the roles of nonhuman stakeholders. Further theoretical and practical work will be necessary to advance the resulting understanding of more-than-human heritage. The examples discussed in this article illustrate some challenges that will be typical for the conceptualisation and capture of nonhuman lifeforms, their behaviours, artefacts, traditions, cultures and habitats. Considering this in application to abiotic nonhumans will be even more difficult but equally important.

The article used large old trees as a test case for more-than-human heritage. Such trees serve as keystone structures within many ecosystems. Their rapid disappearance calls for specific preservation measures. The preservation of living trees and measures that can help their recruitment and survival are of the utmost importance (Lindenmayer et al. 2013). Where such measures are impossible or too slow, artificial replacements provide an alternative. The design and management of such replacements is a complex challenge that must refer to historical ecosystems and their organisms, including trees and arboreal communities.

The article illustrates that capture and preservation of trees, their ecosystems, and the life histories they support can productively challenge existing conceptions of heritage. From this foundation, the article tests common imaging techniques in application to large old trees. The preliminary analysis shows that such techniques can provide useful information. However, complex biological forms and processes are considerably more challenging for the existing methods and equipment than many artificial objects. With trees, a complete continuous capture is usually impossible. The need to capture temporal change presents further difficulties. A combination of techniques will be necessary in most cases. Integration of complementary data sets and their subsequent interpretation require additional processing and integration. Future usage will require well-defined theoretical objectives and dedicated methods. The experiments conducted for this article illustrate the need for further theory construction and technical development. Perhaps most of all, this article emphasizes the value of the surviving more-than-human worlds and exposes the difficulty of recouping the losses.

Acknowledgements

This article uses samples and data from several collaborative projects and the authors thank Alexander Holland and Dan Parker for their contributions.

Authors' contributions

Stanislav Roudavski proposed the idea, conceived of the study, structured the argument, drafted the article and completed the writing. Julian Rutten elaborated the study design, conducted the tests, prepared the visual materials and drafted the article. The authors read and approved the final manuscript.

Funding

The Australia Research Council's Discovery Project grant DP170104010, *Place and Parametricism: Provocations for the Rethinking of Design*, supported the work on the project discussed in this article.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

¹Faculty of Architecture, Building and Planning, The University of Melbourne, Melbourne, Australia. ²Faculty of Health, Arts and Design, The University of Swinburne, Melbourne, Australia.

Received: 20 November 2019 Accepted: 20 January 2020

References

- Amundson, Ron, and George V. Lauder. 1994. Function Without Purpose The Uses of Causal Role Function in Evolutionary Biology. *Biology and Philosophy* 9 (4): 443–469. <https://doi.org/10.1007/BF00850375>.
- Anderson, Eugene Newton, Deborah M. Pearsall, Eugene S. Hunn, and Nancy J. Turner, eds. 2011. *Ethnobiology*. Oxford: Wiley-Blackwell.
- Barthélémy, Daniel, and Yves Caraglio. 2007. Plant Architecture: A Dynamic, Multilevel and Comprehensive Approach to Plant Form, Structure and Ontogeny. *Annals of Botany* 99 (3): 375–407. <https://doi.org/10.1093/aob/mcl260>.
- Bauhus, Jürgen, Kristin Baber, and Jörg Müller. 2018. *Dead Wood in Forest Ecosystems*. Oxford: Oxford University Press. <https://doi.org/10.1093/OBO/9780199830060-0196>.
- Begon, Michael, Colin R. Townsend, and John L. Harper. 1986. 2006. *Ecology: From Individuals to Ecosystems*. 4th ed. Massachusetts: Blackwell.
- Bell, Susan J., Earl D. McCoy, and Henry R. Mushinsky, eds. 1991. *Habitat Structure: The Physical Arrangement of Objects in Space*. Dordrecht: Springer.
- Berg, Jessica. 2007. Of Elephants and Embryos: A Proposed Framework for Legal Personhood. *Hastings Law Journal* 59: 369–406.
- Bock, Walter J., and Gerd von Wahlert. 1965. Adaptation and the Form-Function Complex. *Evolution* 19 (3): 269–299. <https://doi.org/10.2307/2406439>.
- Boonman-Berson, Susan. 2018. Rethinking Wildlife Management. PhD diss., Wageningen: Wageningen University.
- Boyd, Brian. 2017. Archaeology and Human–Animal Relations: Thinking Through Anthropocentrism. *Annual Review of Anthropology* 46 (1): 299–316. <https://doi.org/10.1146/annurev-anthro-102116-041346>.
- Bradshaw, Corey J.A. 2012. Little Left to Lose: Deforestation and Forest Degradation in Australia Since European Colonization. *Journal of Plant Ecology* 5 (1): 109–120. <https://doi.org/10.1093/jpe/rtr038>.
- Brakes, Philippa, Sasha R.X. Dall, Lucy M. Aplin, Stuart Bearhop, Emma L. Carroll, Paolo Ciucci, Vicki Fishlock, et al. 2019. Animal Cultures Matter for Conservation. *Science* 363 (6431): 1032–1034. <https://doi.org/10.1126/science.aaw3557>.
- Brooks, David. 2019. *The Grass Library*. Blochheath: Brandl & Schlesinger.
- Brulotte, Ronda L., and Michael A. Di Giovine. 2014. *Edible Identities: Food as Cultural Heritage*. Burlington: Ashgate.
- Bütler, Rita, Thibault Lachat, Laurent Larrieu, and Yoan Paillet. 2013. Habitat Trees: Key Elements for Forest Biodiversity. In *Integrative Approaches as an Opportunity for the Conservation of Forest Biodiversity*, ed. Daniel Kraus and Frank Krumm, 84–91. Erfurt: European Forest Institute.
- Byrne, Denis, and Gro Bridgit Ween. 2015. Bridging Cultural and Natural Heritage. In *Global Heritage: A Reader*, ed. Lynn Meskell, 94–111. Chichester: Wiley-Blackwell.
- Callicott, Baird J. 2014. *Thinking Like a Planet: The Land Ethic and the Earth Ethic*. New York: Oxford University Press.
- Caro, Tim, and Paul W. Sherman. 2012. Vanishing Behaviors. *Conservation Letters* 5 (3): 159–166. <https://doi.org/10.1111/j.1755-263X.2012.00224.x>.
- Carpaneto, Giuseppe Maria, Adriano Mazziotta, Giorgia Coletti, Luca Luiselli, and Paolo Audisio. 2010. Conflict Between Insect Conservation and Public Safety: The Case Study of a Saproxylid Beetle (*Osmoderma eremita*) in Urban Parks. *Journal of Insect Conservation* 14 (5): 555–565. <https://doi.org/10.1007/s10841-010-9283-5>.
- Chandler, David, and Julian Reid. 2019. *Becoming Indigenous: Governing Imaginaries in the Anthropocene*. London: Rowman & Littlefield.
- Chen, Lovell. 2005. *Burnley Gardens: Conservation Management Plan*. Melbourne: The University of Melbourne.
- Cloke, Paul, and Eric Pawson. 2008. Memorial Trees and Treescape Memories. *Environment and Planning D: Society and Space* 26 (1): 107–122. <https://doi.org/10.1068/d79j>.
- Colloff, Matthew. 2014. *Flooded Forest and Desert Creek: Ecology and History of the River Red Gum*. Collingwood: CSIRO.
- Conway, T.M. 2016. Tending Their Urban Forest: Residents' Motivations for Tree Planting and Removal. *Urban Forestry and Urban Greening* 17: 23–32. <https://doi.org/10.1016/j.ufug.2016.03.008>.
- Cordero-Rivera, Adolfo. 2017. Behavioral Diversity (Ethodiversity): A Neglected Level in the Study of Biodiversity. *Frontiers in Ecology and Evolution* 5: 7. <https://doi.org/10.3389/fevo.2017.00007>.
- Crowther, Thomas W., Henry B. Glick, Kristofer R. Covey, Charlie Bettigole, Daniel S. Maynard, Stephen M. Thomas, Jeffrey R. Smith, et al. 2015. Mapping Tree Density at a Global Scale. *Nature* 525 (7568): 201–205. <https://doi.org/10.1038/nature14967>.
- de la Bellacasa, María Puig, eds. 2017. *Matters of Care: Speculative Ethics in More than Human Worlds*. Minneapolis: University of Minnesota Press.
- DeSilvey, Caitlin, and Rodney Harrison. 2019. Anticipating Loss: Rethinking Endangerment in Heritage Futures. *International Journal of Heritage Studies* 26 (1): 1–7. <https://doi.org/10.1080/13527258.2019.1644530>.
- Dickman, Chris. 2020. *More Than One Billion Animals Impacted in Australian Bushfires*. Vol. 8, 2020. The University of Sydney <https://sydney.edu.au/news-opinion/news/2020/01/08/australian-bushfires-more-than-one-billion-animals-impacted.html>.
- Donaldson, Sue, and Will Kymlicka. 2011. *Zoopolis: A Political Theory of Animal Rights*. New York: Oxford University Press.
- Douglas, Ian, and David Goode, eds. 2011. *The Routledge Handbook of Urban Ecology*. London: Routledge.
- Eddington, John. 2017. *Indigenous Environmental Knowledge: Reappraisal*. New York: Springer.
- Ellen, Roy F., Peter Parkes, and Alan Bicker, eds. 2006. *Indigenous Environmental Knowledge and Its Transformations: Critical Anthropological Perspectives*. London: Routledge.
- Farmer, Jared. 2019. Taking Liberties with Historic Trees. *Journal of American History* 105 (4): 815–842. <https://doi.org/10.1093/jahist/jaz001>.
- Forlano, Laura. 2016. Decentering the Human in the Design of Collaborative Cities. *Design Issues* 32 (3): 42–54. https://doi.org/10.1162/DESI_a_00398.
- Franklin, Adrian. 2017. The More-Than-Human City. *The Sociological Review* 65 (2): 202–217. <https://doi.org/10.1111/1467-954X.12396>.
- Gibbons, Philip, and David B. Lindenmayer. 2002. *Tree Hollows and Wildlife Conservation in Australia*. Collingwood: CSIRO.
- Gibbons, Philip, David B. Lindenmayer, Joern Fischer, Adrian D. Manning, Amit Weinberg, Julian A. Seddon, Patrick R. Ryan, and Gaye Barrett. 2008. The Future of Scattered Trees in Agricultural Landscapes. *Conservation Biology* 22 (5): 1309–1319. <https://doi.org/10.1111/j.1523-1739.2008.00997.x>.
- Gillespie, Kathryn, and Rosemary-Claire Collard. 2015. *Critical Animal Geographies: Politics, Intersections and Hierarchies in a Multispecies World*. London: Routledge.
- Goldingay, Ross. 2009. Characteristics of Tree Hollows Used by Australian Birds and Bats. *Wildlife Research* 36 (5): 394–409. <https://doi.org/10.1071/WR08172>.
- Gould, Stephen Jay, and Elisabeth S. Vrba. 1982. Exaptation: A Missing Term in the Science of Form. *Paleobiology* 8 (1): 4–15. <https://doi.org/10.1017/S0094837300004310>.
- Graham, Brian, Gregory J. Ashworth, and John E. Tumbidge. 2000. *A Geography of Heritage: Power, Culture and Economy*. London: Routledge.
- Guerrant, Edward O., Kayri Havens, and Mike Maunder, eds. 2004. *Ex Situ Plant Conservation: Supporting Species Survival in the Wild*. The Science and Practice of Ecological Restoration. Washington: Island Press.
- Gustafsson, Laura, and Terike Haapoja, eds. 2015. *History According to Cattle*. Brooklin: Punctum.
- Hadley, John. 2017. Animal Property Rights: Justice or Conservation? In *Natural Resources and Environmental Justice: Australian Perspective*, ed. Anna Lukasiewicz, Stephen Dovers, Libby Robin, Jennifer McKay, Steven Schilizzi, and Sonia Graham, 133–142. Clayton South: CSIRO.
- Hamilton, Lindsay, and Nik Taylor. 2017. *Ethnography after Humanism: Power, Politics and Method in Multi-Species Research*. London: Springer.
- Hannan, L., D.S. Le Roux, R.N.C. Milner, and P. Gibbons. 2019. Erecting Dead Trees and Utility Poles to Offset the Loss of Mature Trees. *Biological Conservation* 236 (August): 340–346. <https://doi.org/10.1016/j.biocon.2019.06.001>.

- Harrison, Rodney. 2013a. Forgetting to Remember, Remembering to Forget: Late Modern Heritage Practices, Sustainability and the 'Crisis' of Accumulation of the Past. *International Journal of Heritage Studies* 19 (6): 579–595. <https://doi.org/10.1080/13527258.2012.678371>.
- Harrison, Rodney. 2013b. *Heritage: Critical Approaches*. New York: Routledge.
- Harrison, Rodney. 2015. Beyond 'Natural' and 'Cultural' Heritage: Toward an Ontological Politics of Heritage in the Age of Anthropocene. *Heritage & Society* 8 (1): 24–42. <https://doi.org/10.1179/2159032X15Z.00000000036>.
- Hill, Erica. 2013. Archaeology and Animal Persons: Toward a Prehistory of Human-Animal Relations. *Environment and Society* 4 (1): 117–136. <https://doi.org/10.3167/ares.2013.040108>.
- Holdsworth, David W., and Michael M. Thornton. 2002. Micro-CT in Small Animal and Specimen Imaging. *Trends in Biotechnology* 20 (8): S34–S39. [https://doi.org/10.1016/S0167-7799\(02\)02004-8](https://doi.org/10.1016/S0167-7799(02)02004-8).
- Hsieh, Jiang. 2003. 2009. *Computed Tomography: Principles, Design, Artifacts, and Recent Advances*. 2nd ed. Bellingham: The International Society for Optical Engineering.
- Impey, Chris, Anna H. Spitz, and William R. Stoeger, eds. 2013. *Encountering Life in the Universe: Ethical Foundations and Social Implications of Astrobiology*. Tucson: University of Arizona Press.
- Inglis, Julian. 1993. *Traditional Ecological Knowledge: Concepts and Cases*. Ottawa: International Program on Traditional Ecological Knowledge: International Development Research Centre.
- Isaac, Bronwyn, Raylene Cooke, Daniel Ierodiaconou, and John White. 2014. Does Urbanization Have the Potential to Create an Ecological Trap for Powerful Owls (*Ninox strenua*)? *Biological Conservation* 176: 1–11. <https://doi.org/10.1016/j.biocon.2014.04.013>.
- Kalof, Linda, ed. 2017. *The Oxford Handbook of Animal Studies*. Oxford: Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780199927142.001.0001>.
- Kangas, Patrick C. 2004. *Ecological Engineering: Principles and Practice*. Boca Raton: Lewis Publishers.
- Keller, Eva. 2008. The Banana Plant and the Moon: Conservation and the Malagasy Ethos of Life in Masoala, Madagascar. *American Ethnologist* 35 (4): 650–664.
- Kimmerer, Robin Wall. 2013. *Braiding Sweetgrass*. Minneapolis: Milkweed.
- Kirksey, Eben. 2014. *The Multispecies Salon*, 2014. Durham: Duke University Press.
- Kirshenblatt-Gimblett, Barbara. 1995. Theorizing Heritage. *Ethnomusicology* 39 (3): 367–380. <https://doi.org/10.2307/924627>.
- Krishnan, Sarada. 2016. The Role of Botanic Gardens in the Twenty-First Century. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 11: 023. <https://doi.org/10.1079/PAVSNNR201611023>.
- Kuutma, Kristin. 2009. Cultural Heritage: An Introduction to Entanglements of Knowledge, Politics and Property. *Journal of Ethnology and Folkloristics* 3 (2): 5–12.
- Laiolo, Paola, and Roger Jovani. 2007. The Emergence of Animal Culture Conservation. *Trends in Ecology & Evolution* 22 (1): 5. <https://doi.org/10.1016/j.tree.2006.10.007>.
- Lambert, Ian B. 2012. Geoethics: A Perspective from Australia. *Annals of Geophysics* 55 (3): 377–378. <https://doi.org/10.4401/ag-5556>.
- Latulippe, Nicole. 2015. Situating the Work: A Typology of Traditional Knowledge Literature. *AlterNative: An International Journal of Indigenous Peoples* 11 (2): 118–131. <https://doi.org/10.1177/117718011501100203>.
- Lewi, Hannah, Wally Smith, Andrew Murray, and Steven Cooke. 2016. Visitor, Contributor and Conversationalist: Multiple Digital Identities of the Heritage Citizen. *Historic Environment* 28 (2): 12.
- Lindenmayer, David B. 2009. *Forest Pattern and Ecological Process: A Synthesis of 25 Years of Research*. Melbourne: CSIRO.
- Lindenmayer, David B., Wade Blanchard, Lachlan McBurney, David Blair, Sam Banks, Gene E. Likens, Jerry F. Franklin, William F. Laurance, John A.R. Stein, and Phillip Gibbons. 2012a. Interacting Factors Driving a Major Loss of Large Trees with Cavities in a Forest Ecosystem. *Plos One* 7 (10): e41864. <https://doi.org/10.1371/journal.pone.0041864>.
- Lindenmayer, David B., and William F. Laurance. 2016. The Ecology, Distribution, Conservation and Management of Large Old Trees. *Biological Reviews* 132: 1434–1458. <https://doi.org/10.1111/brv.12290>.
- Lindenmayer, David B., William F. Laurance, and Jerry F. Franklin. 2012b. Global Decline in Large Old Trees. *Science* 338 (6112): 1305–1306. <https://doi.org/10.1126/science.1231070>.
- Lindenmayer, David B., William F. Laurance, Jerry F. Franklin, Gene E. Likens, Sam C. Banks, Wade Blanchard, Phillip Gibbons, et al. 2013. New Policies for Old Trees: Averting a Global Crisis in a Keystone Ecological Structure. *Conservation Letters* 7 (1): 61–69. <https://doi.org/10.1111/conl.12013>.
- Lowry, H el ene, Alan Lill, and Bob B.M. Wong. 2013. Behavioural Responses of Wildlife to Urban Environments. *Biological Reviews* 88 (3): 537–549. <https://doi.org/10.1111/brv.12012>.
- Luhmann, Thomas, Stuart Robson, Stephen Kyle, and Jan Boehm. 2011. *Close-Range Photogrammetry and 3D Imaging*. Caithness: Wittles.
- Maller, Cecily. 2018. *Healthy Urban Environments: More-Than-Human Theories*. London: Routledge.
- Manning, Adrian, Phillip Gibbons, Joern Fischer, Damon Oliver, and David B. Lindenmayer. 2012. Hollow Futures? Tree Decline, Lag Effects and Hollow-Dependent Species. *Animal Conservation* 16 (4): 395–405. <https://doi.org/10.1111/acv.12006>.
- Maser, Chris, Andrew W. Claridge, and James M. Trappe. 2008. *Trees, Truffles, and Beasts: How Forests Function*. New Brunswick: Rutgers University Press.
- Matlock, Marty D., and Robert A. Morgan. 2011. *Ecological Engineering Design: Restoring and Conserving Ecosystem Services*. Hoboken: Wiley.
- McNabb. 1996. Observations on the Biology of the Powerful Owl *Ninox strenua* in Southern Victoria. *Australian Bird Watcher* 17 (7): 267–295.
- Menzies, Charles R., ed. 2006. *Traditional Ecological Knowledge and Natural Resource Management*. Lincoln: University of Nebraska Press.
- Mesoudi, Alex. 2016. Cultural Evolution: A Review of Theory, Findings and Controversies. *Evolutionary Biology* 43 (4): 481–497. <https://doi.org/10.1007/s11692-015-9320-0>.
- Mitchell, Peter. 2018. *The Donkey in Human History: An Archaeological Perspective*. Oxford: Oxford University Press.
- Mitton, Jeffrey B., and Michael C. Grant. 1996. Genetic Variation and the Natural History of Quaking Aspen. *BioScience* 46 (1): 25–31. <https://doi.org/10.2307/1312652>.
- Morris, Richard J., ed. 2018. *Mathematical Modelling in Plant Biology*. Cham: Springer.
- Musselman, Lytton. 2003. Trees in the Koran and the Bible. *Unasylva* 54 (213): 45–52.
- Nelson, Melissa K., and Dan Shilling, eds. 2018. *Traditional Ecological Knowledge: Learning from Indigenous Practices for Environmental Sustainability. New Directions in Sustainability and Society*. Cambridge: Cambridge University Press.
- Niklas, Karl J., and Hanns-Christof Spatz. 2012. *Plant Physics*. Chicago: University of Chicago Press.
- Norkunas, Martha. 2017. Are Trees Spiritual? *Narrative Culture* 4 (2): 169–184.
- O'Bryan, Katharine Mary. 2004. The Appropriation of Indigenous Ecological Knowledge: Recent Australian Developments. *Macquarie Journal of International and Comparative Environmental Law*, no. 1: 29–50.
- Owens, Marcus, and Jennifer Wolch. 2019. Rewilding Cities. In *Rewilding*, ed. Johan T. du Toit, Nathalie Pettorelli, and Sarah M. Durant, 280–302. Cambridge: Cambridge University Press. <https://doi.org/10.1017/9781108560962.014>.
- Pierotti, Raymond John. 2011. *Indigenous Knowledge, Ecology, and Evolutionary Biology*. New York: Routledge.
- Porter, Libby. 2006. Rights or Containment? The Politics of Aboriginal Cultural Heritage in Victoria. *Australian Geographer* 37 (3): 355–374. <https://doi.org/10.1080/00049180600954781>.
- Pritchard, Diana J., John E. Fa, Sara Oldfield, and Stuart R. Harrop. 2012. Bring the Captive Closer to the Wild: Redefining the Role of *Ex Situ* Conservation. *Oryx* 46 (1): 18–23. <https://doi.org/10.1017/S0030605310001766>.
- Prusinkiewicz, Przemyslaw, Mikolaj Cieslak, Pascal Ferraro, and Jim Hanan. 2018. Modeling Plant Development with L-Systems. In *Mathematical Modelling in Plant Biology*, ed. Richard J. Morris, 139–169. Cham: Springer.
- Radu, Stelian. 2006. The Ecological Role of Deadwood in Natural Forests. In *Nature Conservation: Concepts and Practice*, ed. Dan Gafta and John Akeroyd, 137–141. Berlin: Springer https://doi.org/10.1007/978-3-540-47229-2_16.
- Ramos, M. Magda, and Fabio Remondino. 2015. Data Fusion in Cultural Heritage: A Review. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 40 (5): 359–363. <https://doi.org/10.5194/isprsarchives-XL-5-W7-359-2015>.
- Ramsey, Grant. 2013. Culture in Humans and Other Animals. *Biology & Philosophy* 28 (3): 457–479. <https://doi.org/10.1007/s10539-012-9347-x>.
- Remondino, Fabio. 2011. Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. *Remote Sensing* 3 (6): 1104–1138. <https://doi.org/10.3390/rs3061104>.
- Ripple, William J., James A. Estes, Oswald J. Schmitz, Vanessa Constant, Matthew J. Kaylor, Adam Lenz, Jennifer L. Motley, Katharine E. Self, David S. Taylor, and Christopher Wolf. 2016. What is a Trophic Cascade? *Trends in Ecology & Evolution* 31 (11): 842–849. <https://doi.org/10.1016/j.tree.2016.08.010>.

- Rolston, Holmes. 2012. *A New Environmental Ethics: The Next Millennium for Life on Earth*. New York: Routledge.
- Roşca, Sabina, Juha Suomalainen, Harm Bartholomeus, and Martin Herold. 2018. Comparing Terrestrial Laser Scanning and Unmanned Aerial Vehicle Structure from Motion to Assess Top of Canopy Structure in Tropical Forests. *Interface Focus* 8 (2): 20170038. <https://doi.org/10.1098/rsfs.2017.0038>.
- Rosenzweig, Michael L. 2003. Reconciliation Ecology and the Future of Species Diversity. *Oryx* 37 (2): 194–205. <https://doi.org/10.1017/S0030605303000371>.
- Roudavski, Stanislav. 2018. Notes on More-than-Human Architecture. In *Undesign: Critical Practices at the Intersection of Art and Design*, ed. Gretchen Coombs, Andrew McNamara, and Gavin Sade, 24–37. Abingdon: Routledge. <https://doi.org/10.4324/9781315526379>.
- Roudavski, Stanislav, and Dan Parker. 2020. Modelling Workflows for More-than-Human Design: Prosthetic Habitats for the Powerful Owl (*Ninox strenua*). In *Impact - Design with All Senses: Proceedings of the Design Modelling Symposium, Berlin 2019*, ed. Gengnagel, Christoph, Baverel, Olivier, Burry, Jane, Thomsen, Mette Ramsgaard, and Stefan Weinzierl, 554–564. Cham: Springer. https://doi.org/10.1007/978-3-030-29829-6_43.
- Roux, Le, S. Darren, Karen Ikin, David B. Lindenmayer, Gideon Bistricher, Adrian D. Manning, and Philip Gibbons. 2016. Effects of Entrance Size, Tree Size and Landscape Context on Nest Box Occupancy: Considerations for Management and Biodiversity Offsets. *Forest Ecology and Management* 366: 135–142. <https://doi.org/10.1016/j.foreco.2016.02.017>.
- Roux, Le, S. Darren, Karen Ikin, David B. Lindenmayer, Wade Blanchard, Adrian Manning, and Philip Gibbons. 2014. Reduced Availability of Habitat Structures in Urban Landscapes: Implications for Policy and Practice. *Landscape and Urban Planning* 125: 57–64. <https://doi.org/10.1016/j.landurbplan.2014.01.015>.
- Shelton, Dinah. 2015. *Nature as a Legal Person*. *Vertigo* 22 (September). <https://doi.org/10.4000/vertigo.16188>.
- Shmulsky, Rubin, and P. David Jones. 1982. 2011. *Forest Products and Wood Science: An Introduction*. 6th ed. Chichester: Wiley-Blackwell.
- Spennemann, Dirk H.R. 2007. A Line in the Sand? Explorations of the Cultural Heritage Value of Hominid, Pongid, and Robotid Artifacts. *International Journal of Cultural Property* 14 (2): 241–266. <https://doi.org/10.1017/S0940739107070075>.
- State of Victoria. 2019. North East Link Project: Environment Effects Statement: Summary Report. In *Environment Effects Statement*. Melbourne: North East Link Project.
- Sterling, Eleanor J., Christopher Filardi, Anne Toomey, Amanda Sigouin, Erin Betley, Nadav Gazit, Jennifer Newell, et al. 2017. Biocultural Approaches to Well-Being and Sustainability Indicators Across Scales. *Nature Ecology & Evolution* 1 (12): 1798–1806. <https://doi.org/10.1038/s41559-017-0349-6>.
- Stokland, Jogeir N., Juha Siitonen, and Bengt Gunnar Jonsson. 2012. Biodiversity in Dead Wood. In *Ecology, Biodiversity, and Conservation*. New York: Cambridge University Press.
- Tews, Jörg, Ulrich Brose, Volker Grimm, Katja Tielbörger, Matthias C. Wichmann, Monika Schwager, and Florian Jeltsch. 2004. Animal Species Diversity Driven by Habitat Heterogeneity/Diversity: The Importance of Keystone Structures. *Journal of Biogeography* 31 (1): 79–92. <https://doi.org/10.1046/j.0305-0270.2003.00994.x>.
- Thomas, Peter. 2000. 2014. *Trees: Their Natural History*. 2nd ed. Cambridge: Cambridge University Press.
- Timothy, Dallen J., ed. 2016. *Heritage Cuisines: Traditions, Identities and Tourism*. London: Routledge.
- Trubek, Amy B. 2008. The Taste of Place: A Cultural Journey into Terroir. In *California Studies in Food and Culture*. Berkeley: University of California Press.
- Waal, Frans B.M. de. 2017. *Are We Smart Enough to Know How Smart Animals Are?* New York: W. W. Norton.
- Waterton, Emma, and Steve Watson. 2013. Framing Theory: Towards a Critical Imagination in Heritage Studies. *International Journal of Heritage Studies* 19 (6): 546–561. <https://doi.org/10.1080/13527258.2013.779295>.
- Watts, Christopher M., ed. 2013. *Relational Archaeologies: Humans, Animals, Things*. London: Routledge.
- Whitehead, Hal. 2010. Conserving and Managing Animals That Learn Socially and Share Cultures. *Learning & Behavior* 38 (3): 329–336. <https://doi.org/10.3758/LB.38.3.329>.
- Wilkes, J. 1982. Stem Decay in Deciduous Hardwoods: An Overview. *Australian Forestry* 45 (1): 42–50. <https://doi.org/10.1080/00049158.1982.10674330>.
- Winter, Tim. 2013. Clarifying the Critical in Critical Heritage Studies. *International Journal of Heritage Studies* 19 (6): 532–545. <https://doi.org/10.1080/13527258.2012.720997>.
- Wissenburg, Marcel, and David Schlosberg, eds. 2014. *Political Animals and Animal Politics*. Houndmills: Palgrave Macmillan.
- Wolf, Paul R., Bon A. Dewitt, and Benjamin E. Wilkinson. 2000. 2014. *Elements of Photogrammetry with Applications in GIS*. 4th ed. New York: McGraw-Hill Education.
- Wormington, Kevin Ray, David Lamb, Hamish Ian McCallum, and Damien John Moloney. 2003. The Characteristics of Six Species of Living Hollow-Bearing Trees and Their Importance for Arboreal Marsupials in the Dry Sclerophyll Forests of Southeast Queensland, Australia. *Forest Ecology and Management* 182 (1): 75–92. [https://doi.org/10.1016/S0378-1127\(03\)00010-0](https://doi.org/10.1016/S0378-1127(03)00010-0).
- Wright, Katherine. 2017. *Transdisciplinary Journeys in the Anthropocene: More-Than-Human Encounters*. London: Routledge.
- Youatt, Rafi. 2017. Personhood and the Rights of Nature: The New Subjects of Contemporary Earth Politics. *International Political Sociology* 11 (1): 39–54. <https://doi.org/10.1093/ips/olw032>.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)
