

Creating wildlife habitat using artificial structures: a review of their efficacy and potential use in solar farms

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ABSTRACT

The biodiversity crisis is exacerbated by a growing human population modifying nearly three-quarters of the Earth's land surface area for anthropogenic uses. Habitat loss and modification represent the largest threat to biodiversity and finding ways to offset species decline has been a significant undertaking for conservation. Landscape planning and conservation strategies can enhance habitat suitability for biodiversity in human-modified landscapes. Artificial habitat structures such as artificial reefs, nest boxes, chainsaw hollows, artificial burrows, and artificial hibernacula have all been successfully implemented to improve species survival in human-modified and fragmented landscapes. As the global shift towards renewable energy sources continues to rise, the development of photovoltaic systems is growing exponentially. Large-scale renewable projects, such as photovoltaic solar farms have large space requirements and thus have the potential to displace local wildlife. We discuss the feasibility of 'conservoltaic systems' – photovoltaic systems that incorporate elements tailored specifically to enhance wildlife habitat suitability and species conservation. Artificial habitat structures can potentially lessen the impacts of industrial development (e.g., photovoltaic solar farms) through strategic landscape planning and an understanding of local biodiversity requirements to facilitate recolonization.

Key words: artificial habitat, biodiversity, conservoltaic systems, habitat structures, land conversion.

CONTENTS

I. Introduction	1849
II. Methods	1849
III. Artificial habitat for conservation	1850
(1) Macrohabitats	1851
(a) Artificial reefs	1851
(2) Microhabitats	1853
(a) Artificial refugia	1853
(b) Artificial hollows and nest boxes	1853
(c) Bat boxes	1855
IV. Use of artificial structures in solar farms	1855
(1) Renewable energy	1855
(2) Agrivoltaic and conservoltaic systems	1855
V. Management recommendations	1858
VI. Conclusions	1858
VII. Acknowledgements	1859
VIII. References	1859
IX. Supporting information	1867

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I. INTRODUCTION

To support a growing population, it is estimated that over 70% of global land surface area has been modified by anthropogenic land use (Caballero, Ruhoff & Biggs, 2022; Luyssaert *et al.*, 2014). Currently, the global population stands at over 8 billion people, and is expected to exceed 10 billion by the year 2050 (United Nations, 2019). This increase in population has coincided with a shift in land-use practices, as over half of the global population resides in urban areas – with this number expected to rise to 68% by 2050 (United Nations, 2019). Land conversion has largely consisted of converting natural areas into urban and peri-urban areas or agricultural landscapes; over 40% of the Earth's land area is used exclusively for agricultural purposes (Barbier, 2007; Moraes, Mello & Toppa, 2017; Prieto-Benítez & Méndez, 2011). Excessive development and habitat alteration has negatively impacted many ecosystems, with effects on watersheds (i.e., increased damage in the form of erosion, sedimentation, surface runoffs, landslides, and flooding (Fitrian & Wona, 2021; Purba, Slamet & Rauf, 2021)), increased risk of fire and drought (Sloan *et al.*, 2017) and increased greenhouse gas emissions (Caballero *et al.*, 2022). Most notably, land conversion for anthropogenic purposes has caused biodiversity loss due to habitat loss and subsequent species extinctions (Czekajlo *et al.*, 2021; Hasan *et al.*, 2020; Jiang, Fu & Lü, 2020; Krauss *et al.*, 2010; McKinney, 2002; Prieto-Benítez & Méndez, 2011; Rodrigues *et al.*, 2013).

After excessive development and land conversion, many areas are left with only remnant habitat patches for wildlife to persist (Wilson *et al.*, 2016; Yeager *et al.*, 2020). In conjunction with habitat loss, habitat fragmentation is regarded as the greatest threat to species conservation (Niemandt & Greve, 2016; Ntshanga, Procheş & Slingsby, 2021; Palmeirim *et al.*, 2019; Teckentrup, Kramer-Schadt & Jeltsch, 2019), but see Riva, Koper & Fahrig (2024). This is largely due to limited resources in habitat patches leading to smaller population sizes and species isolation – which, in turn, lead to a loss of genetic diversity (Banks-Leite *et al.*, 2020; Bonin, Almany & Jones, 2011; Daichi *et al.*, 2021; Lino *et al.*, 2019).

Habitat destruction, fragmentation, and climate change are all significant contributors to the current biodiversity crisis, which has been labelled as the sixth global mass extinction event (Banks-Leite *et al.*, 2020; Cushman, 2006; Fletcher *et al.*, 2018; Mantyka-Pringle, Martin & Rhodes, 2012). To mitigate species loss in a rapidly developing world, various proposals have been levied to help species persist in anthropogenic landscapes. Notably, land-sparing and land-sharing schemes have been proposed to protect existing habitat and allow species to coexist in human-modified landscapes (Chandler *et al.*, 2013; Kremen, 2015). Land-sparing schemes maximize agricultural yields to set aside land that can be used for conservation purposes rather than agricultural ones (Chandler *et al.*, 2013; Gilroy *et al.*, 2014; Law *et al.*, 2015; von Wehrden *et al.*, 2014). Alternatively, land-sharing

schemes integrate habitat for biodiversity directly within the area used by industry or multiple other purposes (Chandler *et al.*, 2013; Gilroy *et al.*, 2014; von Wehrden *et al.*, 2014). Both techniques, when tailored for species-specific conservation goals, have been successful by maximizing land use for both agricultural and conservation purposes (Caryl *et al.*, 2016; Egan & Mortensen, 2012; Jiang *et al.*, 2017; Mertz & Mertens, 2017).

In addition to land-sparing and sharing schemes, various artificial habitat structures have been introduced in natural areas to aid in conservation and to offset habitat loss due to human development. Some artificial habitat structures have successfully created suitable habitat for flora and fauna and include artificial reefs (Granneman & Steele, 2015; Nauta *et al.*, 2023; Paxton *et al.*, 2017; Pondella, Claisse & Williams, 2022), artificial hibernacula (Bruckerhoff *et al.*, 2021; Dervo, Museth & Skurdal, 2018; Latham & Knowles, 2008; Neave & Moffatt, 2007; Whiting & Booth, 2012; Zappalorti *et al.*, 2014), artificial tree hollows (Goldingay & Stevens, 2009; Griffiths *et al.*, 2017b; Ruegger, 2018; Voigt *et al.*, 2014), and artificial burrows (Ebrahimi, Fenner & Bull, 2012; Grillet *et al.*, 2010; Lettink & Cree, 2007; Staugas *et al.*, 2013). While natural versions of these structures are preferable in all cases, when unavailable, artificial habitat structures have been deemed suitable substitutes as a source of habitat rehabilitation (Bruckerhoff *et al.*, 2021; Higgins, Metaxas & Scheibling, 2022; Ruegger, 2018; Whiting & Booth, 2012; Zappalorti *et al.*, 2014).

Nearly a quarter of the Earth's land surface area is designated as 'degraded land' (low-productivity landscapes largely unsuitable for agricultural purposes), and it is on this land where significant investments should be made in the construction of renewable energy sources – particularly solar farms (Hernandez *et al.*, 2014; Nordberg, Caley & Schwarzkopf, 2021). It has been suggested that the novel structures intrinsic to photovoltaic systems could provide suitable habitat for biodiversity by increasing structural complexity, providing new opportunities for shelter and the formation of new microclimates (Nordberg *et al.*, 2021; Sinha *et al.*, 2018). During the construction of photovoltaic systems, wildlife can be displaced, and the construction can infringe upon natural habitat features such as burrows and hollow-bearing trees (Hernandez *et al.*, 2014). Thus, it is important to monitor the impacts of solar farms on ecological systems and explore how artificial habitat structures could be used to make these systems more hospitable for wildlife. Herein, we review the use and effectiveness of various artificial habitat techniques globally, in an attempt to determine how these techniques can potentially be applied to commercial-scale solar farms.

II. METHODS

Systematic literature searches were conducted in two academic databases (*Primo* and *Web of Science*) between October 1st 2022, and December 31st 2022. These searches focused

primarily on multi-purpose facilitation within photovoltaic systems, and artificial habitat structures. The first 200 results for each search term (Table 1) were considered for inclusion, as the relevance of subsequent papers diminished after this point. In total, 1870 texts were sourced using these means (Fig. 1). Additional literature (370 texts) that was not located during these searches but was identified *via* recommendations or by searching the reference lists of the sourced literature, were also included through to December 31st, 2023. These additional texts were not identified in the primary search as they lacked the key words (e.g. ‘artificial’) to be located by our search terms. However, searching of reference lists from previous papers and reviews allowed these papers to be included, making this review more comprehensive.

After sources were filtered based on title relevance and duplicates were removed, 171 texts remained. These were classified into one of six categories based on research content (agrivoltaic systems, artificial burrows, artificial hibernacula, artificial hollows, artificial reefs, and solar farms) and organized using the reference manager *Zotero*. The abstracts and full text of these sources, and those of the additional 370 texts added from other sources (see above), were screened to ensure they met the inclusion criteria. Studies were included that satisfied at least one of two conditions: (i) the study detailed the development, implementation, and results of artificial habitat structures for wildlife; or (ii) it detailed the use of photovoltaic systems for secondary purposes (namely agrivoltaic and conservoltaic systems). Studies on artificial habitat structures were included if they focused primarily on conservation-focused efforts for vertebrates. Artificial habitat structures used primarily as a sampling method rather than conservation methods were not included. Review articles, theses, and reports were included in the literature search to enhance our understanding of the efficacy of artificial habitat structures globally. After this screening process, a final total of 401 studies was used as information sources for our systematic review of artificial habitats and their

application in solar farms (included studies are identified with a * symbol in the reference list).

III. ARTIFICIAL HABITAT FOR CONSERVATION

Habitat degradation often results in the loss of natural habitat features, leaving species to attempt to find alternatives which may or may not meet the requirements necessary to support them (Higgins *et al.*, 2022; Zappalorti & Reinert, 1994). As a result, artificial habitat structures have become increasingly important to aid in the conservation of targeted species (Cowan *et al.*, 2021; Ruegger, 2018; Whiting & Booth, 2012). Artificial versions of reefs, hibernacula, burrows, and nest hollows are just some examples of artificial habitat structures that have been shown to augment

Table 1. Search terms used in *Primo* and *Web of Science* and the number of papers included in our database for each term.

Search term	Database	
	Primo	Web of Science
Artificial hibernacula	42	26
Artificial hollows AND bats/ possums/glidens	47	45
Burrows AND skinks/desert tortoises	154	149
Solar farms AND wildlife	42	26
Solar panels AND wildlife	48	32
Agrivoltaic	174	127
Artificial reefs reviews	10	146
Conservoltaic	1	1
Artificial reefs	200	200
Artificial burrows	200	200
Total	918	952

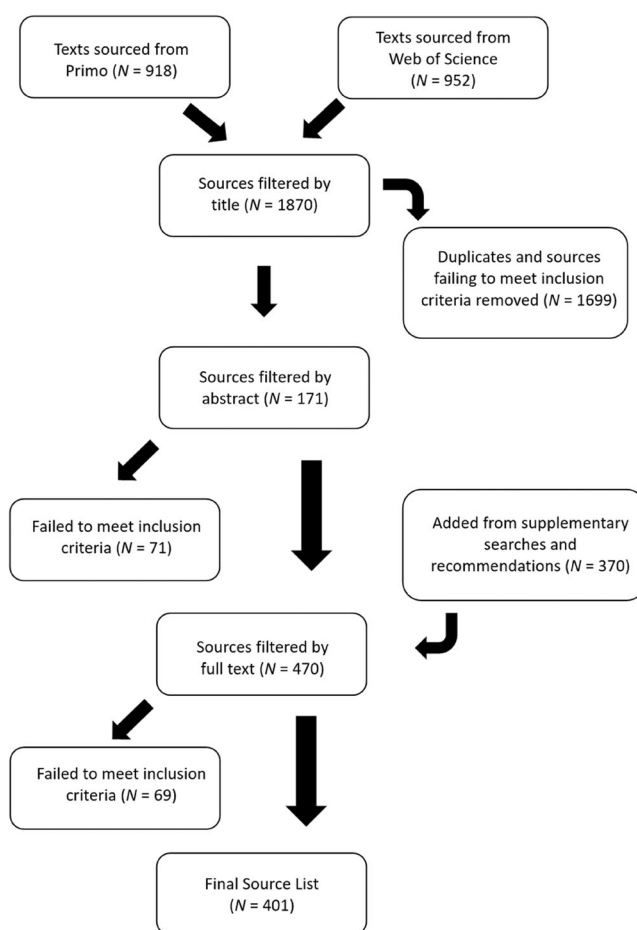


Fig. 1. Screening process for a systematic review of the literature on photovoltaic systems, artificial habitat structures, and conservation in human-modified landscapes. See Table 1 for search terms. Papers added from supplementary searches refers to papers that were identified and filtered from the reference lists of papers identified from primary searches. Most of these papers did not appear in the original search as they lacked key search terms, e.g. ‘artificial’.

habitat suitability (Fig. 2). When targeted for species of concern, artificial habitat structures can provide suitable alternatives to natural habitat features upon which these species rely (Higgins *et al.*, 2022; Ruegger, 2018; Watchorn *et al.*, 2022; Watchorn, Duncan & Cowan, 2023; Whiting & Booth, 2012). The success of these implemented artificial habitat structures in habitats which have been altered due to human interference provides optimism that these methods can be applied in other landscapes to achieve similar goals.

(1) Macrohabitats

Large-scale endeavours to enhance or restore existing ecosystems, or to modify landscapes denoted for human use to become more suitable for wildlife, have been undertaken. On a macroscale, interventions and modifications can be tailored to support a large array of different species. These

systems can be crucial to support biodiversity in areas which have previously, or would otherwise have been, negatively impacted by anthropogenic disturbances.

(a) Artificial reefs

Coral reefs are important habitats in marine ecosystems, providing structure, shelter, food, and nurseries for countless species (Gladfelter, Ogden & Gladfelter, 1980; Graham & Nash, 2013; Hughes *et al.*, 2017; Nagelkerken *et al.*, 2000; Urbina-Barreto *et al.*, 2021). However, coral reefs are vulnerable to climate change, ocean acidification, bleaching, pollution, overfishing, and a variety of biological factors which together have resulted in a drastic global decline in the cover of coral reefs in the last few decades (Abelson & Shlesinger, 2002; Heron *et al.*, 2016; Higgins *et al.*, 2022; Hoegh-Guldberg *et al.*, 2007; Hughes *et al.*, 2017;

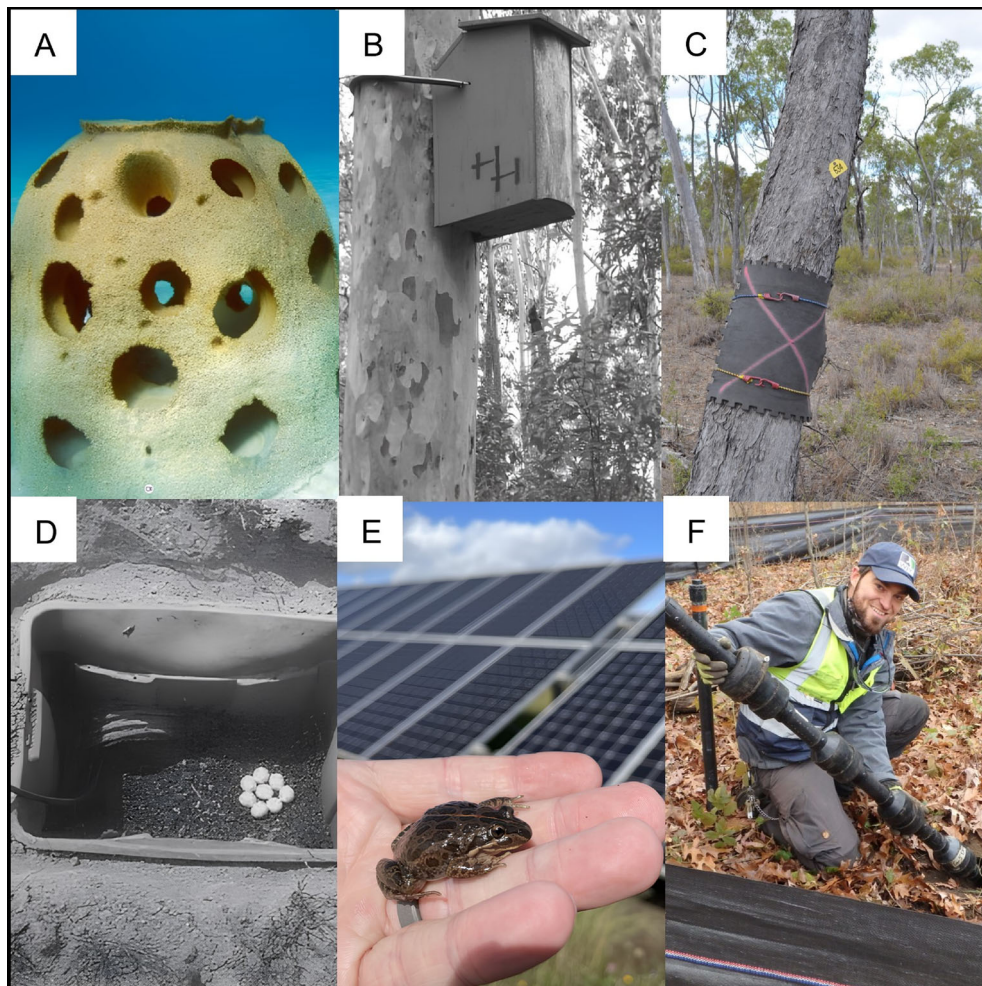


Fig. 2. (A) An artificial reef ball deployed off the coast of the Bahamas (Layman & Allgeier, 2020). (B) A rear-entrance nest box in New South Wales (Beyer & Goldingay, 2006). (C) Artificial bark cover for arboreal lizards in Northern Queensland (Nordberg & Schwarzkopf, 2015). (D) An artificial burrow in Idaho with a clutch of burrowing owl (*Athene cunicularia*) eggs (Belthoff & Smith, 2003). (E) A spotted marsh frog (*Limnodynastes tasmaniensis*) found under solar panels in New South Wales (photograph credit: Eric Nordberg). (F) Artificial hibernation tube for over-wintering snakes in Ontario being installed (photograph credit: Wildlife Preservation Canada).

Paxton *et al.*, 2020; Perkol-Finkel, Shashar & Benayhu, 2006). Artificial reefs, defined as any structure submerged in a body of water to replicate some of the ecosystem services provided by natural reefs (Hackradt, Félix-Hackradt & García-Charton, 2011; Layman & Allgeier, 2020; Paxton *et al.*, 2020), have been shown to be important for fisheries management (Baine, 2001; Bombace *et al.*, 1994; Kelch *et al.*, 1999; McLean *et al.*, 2015; Pan *et al.*, 2022; Santos, Monteiro & Leitão, 2011), conservation (Creque *et al.*, 2006; Higgins *et al.*, 2022; Hughes *et al.*, 2017), and habitat enhancement and restoration (Abelson & Shlesinger, 2002; Becker *et al.*, 2018; Komyakova, Chamberlain & Swearer, 2021;

Perkol-Finkel *et al.*, 2006; Pondella *et al.*, 2022; Tessier *et al.*, 2015) (Table 2).

When planning for the installation of artificial reefs, the conservation goals, materials (eco-friendly synthetic materials are becoming increasingly popular as opposed to traditional rubber, rock, and concrete; Pan *et al.*, 2022), and site selection (Ambrose & Swarbrick, 1989; Creque *et al.*, 2006; Paxton *et al.*, 2020) are important considerations, but the most important factor is the structural complexity of the artificial reef (Granneman & Steele, 2015; Hackradt *et al.*, 2011; Paxton *et al.*, 2017, 2019; Perkol-Finkel *et al.*, 2006; Pondella *et al.*, 2022). Properly designed artificial reefs can

Table 2. Summary of the key benefits from the five major categories of artificial habitat structures detailed in this review.

Habitat	Key benefits	References
Artificial reefs	Aids in conservation	Ambrose & Swarbrick (1989); Creque <i>et al.</i> (2006); Higgins <i>et al.</i> (2022)
	Provides shelter	Houghton (2014); Lima <i>et al.</i> (2019); Nauta <i>et al.</i> (2023); Santos <i>et al.</i> (2011); Urbina-Barreto <i>et al.</i> (2021)
	Source of food	Gladfelter <i>et al.</i> (1980); Nauta <i>et al.</i> (2023); Santos <i>et al.</i> (2011)
	Provides nurseries	Higgins <i>et al.</i> (2022); Nagelkerken <i>et al.</i> (2000); Santos <i>et al.</i> (2011)
	Enhances fisheries	Baine (2001); Bombace <i>et al.</i> (1994); Kelch <i>et al.</i> (1999); McLean <i>et al.</i> (2015); Pan <i>et al.</i> (2022)
	Restores degraded habitat	Abelson & Shlesinger (2002); Becker <i>et al.</i> (2018); Komyakova <i>et al.</i> (2021); Perkol-Finkel <i>et al.</i> (2006); Tessier <i>et al.</i> (2015)
	Provides structural complexity	Graham & Nash (2013); Granneman & Steele (2015); Hackradt <i>et al.</i> (2011); Paxton <i>et al.</i> (2017); Pondella <i>et al.</i> (2022)
Artificial hibernaculum	Increases production of ecosystem	Ambrose & Swarbrick (1989); Layman & Allgeier (2020); Paxton <i>et al.</i> (2019, 2020); Pondella <i>et al.</i> (2022)
	Aids in conservation	Bruckerhoff <i>et al.</i> (2021); Dervo <i>et al.</i> (2018); Latham & Knowles (2008); Shoemaker (2007); Whiting & Booth (2012)
Artificial burrows	Provides long-term overwintering sites	Bruckerhoff <i>et al.</i> (2021); Dervo <i>et al.</i> (2018); Neave & Moffatt (2007); Whiting & Booth (2012); Zappalorti <i>et al.</i> (2014)
	Aids in conservation	Belthoff & Smith (2003); Bourgeois <i>et al.</i> (2015); Ebrahimi <i>et al.</i> (2012); Lettink & Cree (2007); Milne <i>et al.</i> (2003a)
	Provides shelter	Davis & Theimer (2003); Fenner & Bull (2011); Grillet <i>et al.</i> (2010); Milne <i>et al.</i> (2003b); Staugas <i>et al.</i> (2013)
	Provides basking habitat	Ebrahimi <i>et al.</i> (2012); Grillet <i>et al.</i> (2010); Milne <i>et al.</i> (2003b); Milne & Bull (2000); Staugas <i>et al.</i> (2013)
	Can be used as nurseries	Belthoff & Smith (2003); Bourgeois <i>et al.</i> (2015); Menzel (2018); Sutherland <i>et al.</i> (2014)
Artificial hollows/ nest boxes	Provides hunting ground	Milne <i>et al.</i> (2003b)
	Aids in conservation	Harley (2006); Lalas <i>et al.</i> (1999); Libois <i>et al.</i> (2012); Lindenmayer <i>et al.</i> (2016); Menkhorst (1984)
	Provides shelter	Callan <i>et al.</i> (2023); Croose <i>et al.</i> (2016); de Raad <i>et al.</i> (2021); Ellis <i>et al.</i> (2022); Griffiths <i>et al.</i> (2020b)
	Provides nesting sites	Brazill-Boast <i>et al.</i> (2013); Briskie <i>et al.</i> (2014); Dailey (2003); Durant <i>et al.</i> (2009); Griffith <i>et al.</i> (2008)
Bat boxes	Provides hibernacula	Geiser (1987)
	Avenue for species reintroduction	Moseby <i>et al.</i> (2020)
	Increases habitat connectivity	Beyer & Goldingay (2006); Delheimer <i>et al.</i> (2018)
	Aids in conservation	Boyd & Stebbings (1989); Lourenço & Palmeirim (2004); Ruegger <i>et al.</i> (2020); Smith & Agnew (2002); Velasco <i>et al.</i> (2023)
	Provides shelter for torpor	Bartonicka & Rehack (2007); Campbell <i>et al.</i> (2010); Fukui <i>et al.</i> (2010); Gulickx <i>et al.</i> (2007); Kerth <i>et al.</i> (2001)
	Provides maternity roosts	Brittingham & Williams (2000); De La Cruz <i>et al.</i> (2018); Garland <i>et al.</i> (2017); Lourenço & Palmeirim (2004); Ruegger (2016)
	Provides resting stops during migration	Baranauskas (2010); Chytil (2014); Jankowska-Jarek <i>et al.</i> (2023); Low (2017); Voigt <i>et al.</i> (2014)

not only mimic key characteristics of natural reefs, but they can also incorporate more complex structures than natural reefs, allowing for a greater number of microhabitats for marine species to colonize (Granneman & Steele, 2015; Paxton *et al.*, 2017; Pondella *et al.*, 2022). Colonization of these reefs can be rapid [within 1–6 months (Bombace *et al.*, 1994; Creque *et al.*, 2006; Houghton, 2014)], with species richness continuing to increase for years after construction (Abelson & Shlesinger, 2002; Tessier *et al.*, 2015).

Artificial reefs have been used extensively in the Atlantic, Pacific, and Indian Oceans (Granneman & Steele, 2015; Hackradt *et al.*, 2011; Higgins *et al.*, 2022; Pan *et al.*, 2022; Paxton *et al.*, 2017, 2019), the Caribbean (Layman & Allgeier, 2020), the Great Lakes (Creque *et al.*, 2006; Houghton, 2014; Kelch *et al.*, 1999; McLean *et al.*, 2015), and Europe (Bombace *et al.*, 1994; Paxton *et al.*, 2020; Pondella *et al.*, 2022; Santos *et al.*, 2011; Tessier *et al.*, 2015) (Fig. 3). The most successful artificial reef deployments need to be tailor-made for the ecosystem, with common failures of artificial reef projects associated with poor design and improper surveying techniques (Baine, 2001; Higgins *et al.*, 2022; Komyakova *et al.*, 2021; McLean *et al.*, 2015). Deploying artificial reefs with a poor design may fail to attract target species (Baine, 2001; Higgins *et al.*, 2022), attract non-target species (Komyakova *et al.*, 2021), or fail to attract any species (McLean *et al.*, 2015). Like all other artificial habitats, artificial reefs aimed to improve conservation outcomes must carefully select materials for their site and stated goals (Higgins *et al.*, 2022; McLean *et al.*, 2015; Paxton *et al.*, 2020; Santos *et al.*, 2011; Tessier *et al.*, 2015). For example, aggregate concrete has been associated with greater ecological value than rubbers/plastics and tyres which can leach hazardous chemicals into the environment (Higgins *et al.*, 2022).

When special care has been taken to incorporate ecological requirements, artificial reefs can match, and in some cases exceed natural reefs in species richness and abundance (Abelson & Shlesinger, 2002; Creque *et al.*, 2006; Hackradt *et al.*, 2011; Higgins *et al.*, 2022; Houghton, 2014; Kelch *et al.*, 1999; McLean *et al.*, 2015; Tessier *et al.*, 2015), biomass (Layman & Allgeier, 2020; Paxton *et al.*, 2019; Pondella *et al.*, 2022), and diversity (Ambrose & Swarbrick, 1989; Bombace *et al.*, 1994; Granneman & Steele, 2015; Paxton *et al.*, 2020). Artificial structures can also become spawning sites for fish, as structural complexity has been positively correlated with spawning aggregations (Pondella *et al.*, 2022). Complex reef structures, which attract a greater diversity of species, have been linked with increases in primary and secondary productivity, driving positive feedback loops, and further increasing productivity (Layman & Allgeier, 2020; Pondella *et al.*, 2022). This increase in productivity has been associated with better body condition and higher survival rates in fish (Komyakova *et al.*, 2021; Layman & Allgeier, 2020). Thus, artificial reefs, when properly designed, can be effective tools for habitat enhancement and conservation (Paxton *et al.*, 2020).

(2) Microhabitats

Within larger-scale environments, species-specific interventions can also be used to improve conservation outcomes. These features vary in scope, location, purpose, and effectiveness, but when properly incorporated can enhance existing habitats.

(a) Artificial refugia

Conservation actions for herpetofauna, particularly at their northern range limits, present unique challenges as many species use refuges to survive unsuitable surface temperatures during winter (Bruckerhoff *et al.*, 2021). Overwintering sites (i.e., hibernacula) vary depending on species and location, but often consist of rock or log piles, caves, and burrows. Artificial hibernacula do not always attract the targeted species; however, other non-target amphibian and reptile species may use these artificial hibernacula, indicating that they are effective at providing suitable overwintering sites for herpetofauna (Latham & Knowles, 2008; Neave & Moffatt, 2007; Zappalorti *et al.*, 2014). The availability of existing hibernacula is a limiting factor in the usage of artificial hibernacula by herpetofauna, so protecting existing habitats and hibernation sites remains a priority for herpetofauna conservation (Latham & Knowles, 2008). Artificial hibernacula can, however, enhance impoverished environments or provide additional overwintering sites (Latham & Knowles, 2008).

Burrows are an important habitat feature for various species, including reptiles (Ebrahimi *et al.*, 2012; Fenner & Bull, 2011; Grillet *et al.*, 2010; Mensforth & Bull, 2008; Milne, Bull & Hutchinson, 2003b; Milne & Bull, 2000; Staugas *et al.*, 2013), birds (Belthoff & Smith, 2003; Bourgeois *et al.*, 2015; Menzel, 2018; Nadeau, Conway & Rathbun, 2015; Smith, Conway & Ellis, 2005; Sutherland, Dann & Jessop, 2014), and mammals (Davis & Theimer, 2003; Soholt, 1974). For reptiles, burrows provide shelter from predators and environmental hazards (i.e., desiccation, overheating/freezing), a safe retreat site while basking, and hunting sites to ambush prey. Individuals will defend their burrow against competitors (Fenner & Bull, 2011; Grillet *et al.*, 2010; Milne *et al.*, 2003b; Staugas *et al.*, 2013). For burrowing owls and seabirds, artificial burrows provide safe nesting sites with broadly similar breeding success to natural burrows (Belthoff & Smith, 2003; Bourgeois *et al.*, 2015; Menzel, 2018; Sutherland *et al.*, 2014). Artificial burrows and refuges are often used for conservation purposes and can successfully enhance habitats with inadequate availability of natural structures (Ebrahimi *et al.*, 2012; Grillet *et al.*, 2010; Lettink & Cree, 2007; Staugas *et al.*, 2013). The most successful artificial burrows and refuges incorporate features and dimensions of natural structures (Lettink & Cree, 2007; Milne & Bull, 2000; Staugas *et al.*, 2013).

(b) Artificial hollows and nest boxes

Land-clearing and forestry has reduced the availability of natural nest hollows globally (Eyre *et al.*, 2010; Newton, 1994).

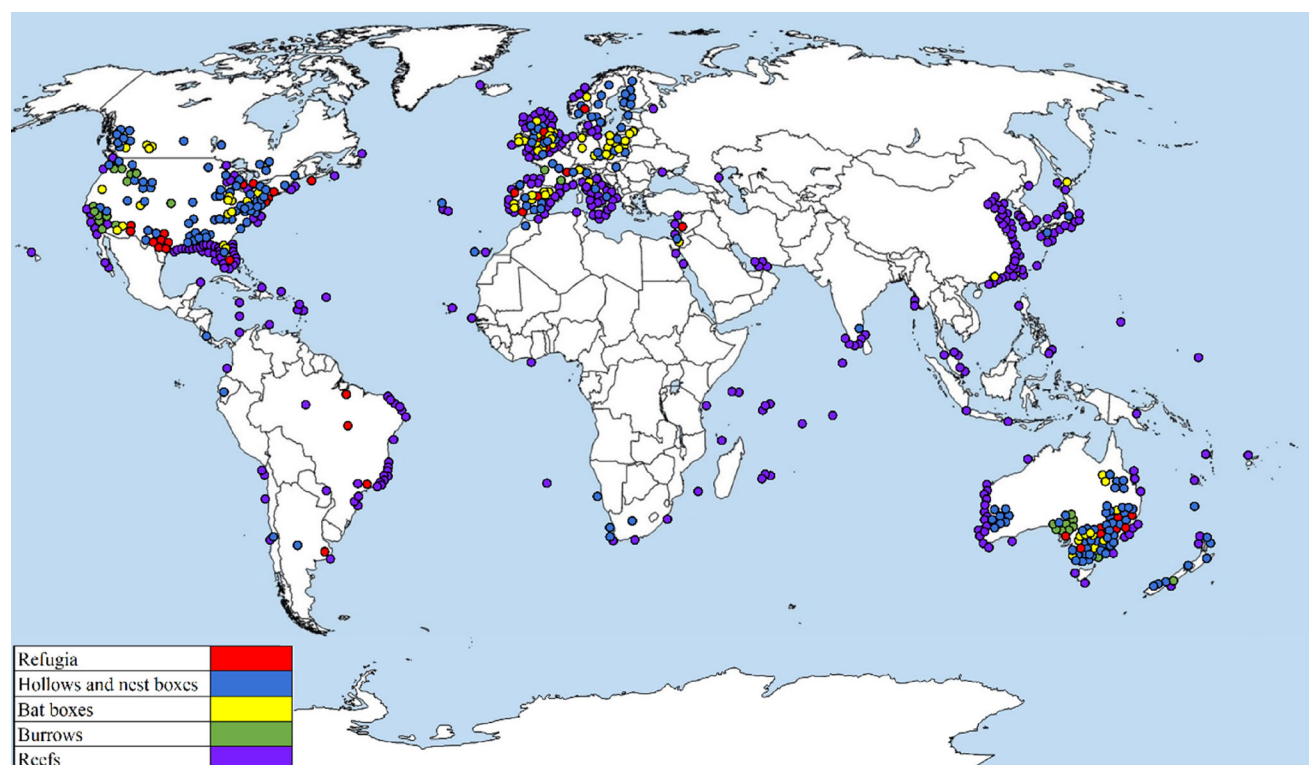


Fig. 3. Global map of artificial habitat structures designed primarily for vertebrate species. Points represent studies on artificial refugia (hibernacula, rock piles, dens; red), artificial hollows and nest boxes (blue), bat boxes and roosts (yellow), artificial burrows (green), and artificial reefs (purple; including studies reviewed by Lima *et al.*, 2019). The studies used to create this figure are provided as online Supporting Information in Table S1.

Natural hollows can take hundreds of years to form, especially where there are few vertebrates that create hollows themselves (Vesk *et al.*, 2008). Therefore, artificial tree hollows can represent an important conservation tool for birds and mammals, as has been shown in Australia (Brazill-Boast, Pryke & Griffith, 2013; Goldingay & Stevens, 2009; Harley, 2006; Rueegger, Goldingay & Brookes, 2013; Saunders *et al.*, 2020), Europe (Bleu, Agostini & Biard, 2017; Bux, Giglio & Gustin, 2008; Czeszczewik, 2004; Fargallo *et al.*, 2001; Klein *et al.*, 2007), and North America (Bortolotti, 1994; Carey, 2002; Dailey, 2003; Dale *et al.*, 2021; Stone *et al.*, 1996). Artificial hollows can provide shelter (Goldingay, 2017; Menkhorst, 1984), nesting sites (Rueegger *et al.*, 2013), hibernacula (Geiser, 1987), and a safe place to reproduce and rear young (Rueegger, 2018). Concerns have been raised regarding the ability of artificial hollows to provide habitat for species of conservation concern, particularly relating to the use of nest boxes by common species rather than the targeted species, and measures have been implemented to improve conservation outcomes (Goldingay, 2020; Griffiths *et al.*, 2017b; Lindenmayer *et al.*, 2016; McComb *et al.*, 2022; Rueegger, 2016, 2018). In particular, the design of nest boxes (Goldingay *et al.*, 2015; Lindenmayer *et al.*, 2003; Rueegger, 2016), thermal requirements (Goldingay & Thomas, 2021; McComb *et al.*, 2022; Rowland, Briscoe & Handasyde, 2017), and alternatives

to traditional artificial hollows have been discussed (Goldingay, Rohweder & Taylor, 2020; Rueegger, 2018).

Nest boxes are particularly useful in areas lacking natural alternatives to create hollows *en masse* (Beyer & Goldingay, 2006; Goldingay *et al.*, 2015, 2020; Harley, 2006; Lindenmayer *et al.*, 2003; Menkhorst, 1984; Moseby *et al.*, 2020; Rueegger *et al.*, 2013). While nest boxes have been identified as important for species reintroduction (Moseby *et al.*, 2020), population growth (Rueegger, 2016), and to increase habitat connectivity (Beyer & Goldingay, 2006), variation in usage among studies demonstrates that there are several factors that determine their success.

Firstly, the location at which nest boxes are placed is important (McClure, Pauli & Heath, 2017). For example, in Australia, marsupials demonstrate a strong preference for natural hollows over artificial hollows, with the latter more effective in areas where natural hollows are lacking (Goldingay *et al.*, 2020; Lindenmayer *et al.*, 2003, 2009; Menkhorst, 1984; Moseby *et al.*, 2020; Rueegger *et al.*, 2013; Smith & Agnew, 2002). Secondly, the dimensions and orientation of the artificial hollows must be considered. For example, while not all marsupials express a preference for the height of nest boxes, the height of artificial hollows particularly for gliders (which prefer heights between 4 and 8 m) should be appropriate for predator avoidance and access (Menkhorst, 1984).

Recently, artificial hollows carved out by chainsaws have been used as an alternative approach to classical nest boxes (Griffiths *et al.*, 2018, 2020b; Rueegger, 2018; Terry, Goldingay & van der Ree, 2021). These chainsaw hollows mimic the thermal properties of natural hollows far better than do nest boxes, being warmer in winter and much cooler in summer than nest boxes (Griffiths *et al.*, 2018; Griffiths, Robert & Jones, 2022; McComb *et al.*, 2022). Chainsaw hollow uptake by marsupials can be relatively rapid: between 19 and 35 days depending on the species (Rueegger, 2018), and have occupancy rates at least equal to, and in some cases higher, than nest boxes (Griffiths *et al.*, 2018, 2020b; Terry *et al.*, 2021). Nest boxes generally have a lifespan of 10–15 years, however, this can be extended *via* routine (yet infrequent) maintenance (Goldingay, 2020; Goldingay, Thomas & Shanty, 2018; Quin *et al.*, 2021). By contrast, chainsaw hollows are relatively permanent fixtures in the environment, with minor enhancements only necessary in cases of revegetation (Harley, 2006; Terry *et al.*, 2021), fungal infection or water accumulation (Carey & Sanderson, 1981). Recent improvements in the design of chainsaw-carved hollows include drilling an entry hole suited for the target species directly into a tree (Ellis, Taylor & Rhind, 2022).

(c) Bat boxes

Bat boxes provide similar benefits to those discussed above for nest boxes, by creating shelter for colonies and maternity roosts (Boyd & Stebbings, 1989; Rueegger, 2016). Bat boxes also provide an added benefit of providing resting sites for migratory species, which can improve their survival, particularly along migratory routes with a lack of natural hollows (Voigt *et al.*, 2014).

The design and placement of bat boxes for target species must be carefully considered as studies have shown that the majority of bat boxes are used by common bat species; therefore, conservation programs targeting at-risk species should be designed to exclude or limit occupancy by common or non-target species (Griffiths *et al.*, 2017a; López-Baucells *et al.*, 2017; Rueegger, 2016; Rueegger *et al.*, 2020; Velasco *et al.*, 2023). Bat boxes should allow side-by-side roosting and must have suitable thermal properties (Brittingham & Williams, 2000; Rueegger, 2016). While properly designed and maintained bat boxes can be important and useful tools for conservation, the enhancement and protection of natural hollows should still be prioritized (Flaquer, Torre & Ruiz-Jarillo, 2006; Rueegger, 2016; Voigt *et al.*, 2014).

IV. USE OF ARTIFICIAL STRUCTURES IN SOLAR FARMS

While the presence of natural habitat features is preferable to the use of artificial habitat structures, when these natural habitat features are absent, inadequate, or have been

destroyed by development, the implementation of artificial structures tailored for target species can help lessen the impact of habitat loss and fragmentation. These artificial habitat structures may also be successful in promoting the recolonization of habitats by previously displaced species.

(1) Renewable energy

Renewable energy production is continuing to rise as the world increasingly shifts away from fossil-fuel energy sources and towards renewable technology (Figs 4 and 5) (Walston *et al.*, 2016). Photovoltaic systems are one source of green energy production: they have low carbon emissions, require less maintenance than alternative renewable energy infrastructure, and can generate economic value from otherwise degraded lands (Dhar *et al.*, 2020; Nordberg *et al.*, 2021). Photovoltaic development has significant economic benefits and can promote energy independence for rural regions (Dhar *et al.*, 2020). Additionally, photovoltaic systems can be used in tandem with other agricultural or conservation-oriented goals. As competition for land use continues to increase and the population of humans continues to climb, using land for multiple purposes is of paramount importance (Hernandez *et al.*, 2014; Nordberg *et al.*, 2021). Nature-based solutions have been proposed as a pathway to tackle the climate crisis and ecological crisis simultaneously (Kabisch *et al.*, 2017).

(2) Agrivoltaic and conservoltaic systems

An increasingly common method to maximize land-sharing between agriculture and solar farms is to incorporate crop growth or livestock grazing in an 'agrivoltaic' system (Adeh, Selker & Higgins, 2018; Amaducci, Yin & Colauzzi, 2018; Campana *et al.*, 2021; Cosgun, 2021; Ezzaeri *et al.*, 2018; Giri & Mohanty, 2022a,b; Gonocruz *et al.*, 2021; Graham *et al.*, 2021; Kumpanalaisatit *et al.*, 2022; Mamun *et al.*, 2022; Marrou *et al.*, 2013a,b; Zainol Abidin, Mahyuddin & Mohd Zainuri, 2021). Combining crop growth and photovoltaic systems increases land productivity by 60–70% and increases the economic value of the land by up to 30% compared to conventional farming (Dinesh & Pearce, 2016; Dupraz *et al.*, 2011; Valle *et al.*, 2017). Additionally, the use of grazing livestock (such as sheep) or native herbivores can provide cheap vegetation management, managing the length of grasses and reducing the risk of fire, as well as presenting solar farmers with an opportunity to take advantage of biodiversity incentives (Nordberg *et al.*, 2021).

In addition to being combined with agriculture, photovoltaic systems can also be used to enhance conservation measures – termed conservoltaic systems (or ecovoltaic systems) (Nordberg & Schwarzkopf, 2023; Tölgyesi *et al.*, 2023). Conservoltaic systems not only benefit wildlife, but can also provide economic benefits for the solar farm itself (Table 3; Turney & Fthenakis, 2011). Native vegetation growth underneath solar panels can reduce the degradation of solar panel backsheets, reduce dust accumulation on the

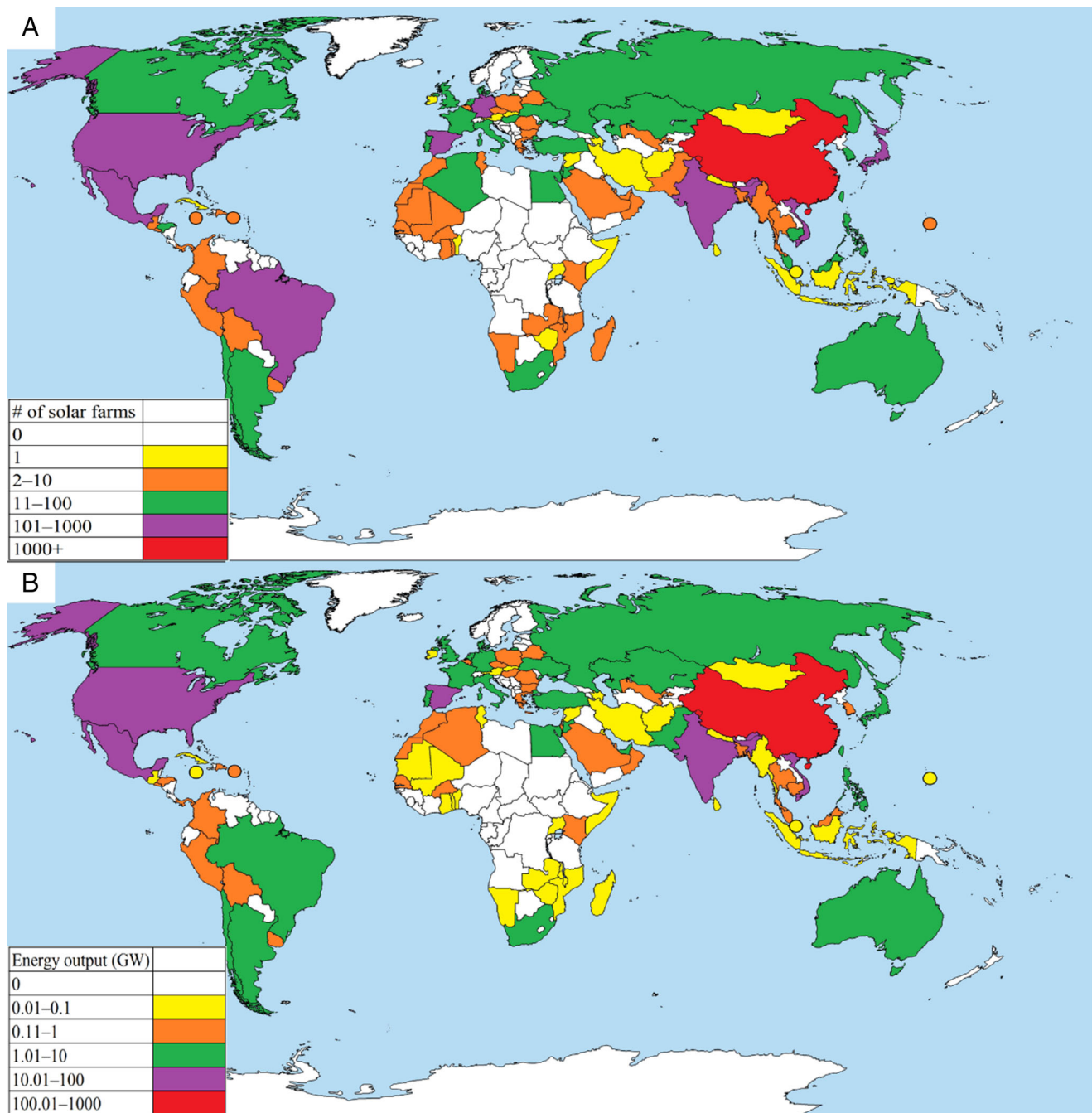


Fig. 4. Global maps of (A) total number of operational photovoltaic (PV) solar farms and (B) total energy output (gigawatt; GW) by country and territory according to Global Energy Monitor (<https://globalenergymonitor.org>). Solar farms with energy production greater than 20 MW (10 MW in select countries in the Middle East and North Africa due to the methodology provided by Global Energy Monitor) were included. Countries in white either have no recorded solar farms or no data available. The data used to create this map can be found at the Global Solar Power Tracker, Global Energy Monitor (<https://globalenergymonitor.org>) May 2023 release ‘Solar Farm Phase Count by Country’ and ‘Solar Farm Capacity (MW) by Country’ summary tables.

panels and thereby improve their efficiency, reduce ambient temperature, and provide habitat to native wildlife including key species such as pollinators (Nordberg *et al.*, 2021; Semeraro *et al.*, 2018).

Construction of solar farms often occurs on degraded land, and the introduction of solar panel arrays increases the structural complexity of the landscape potentially creating new conditions for local wildlife through the provision of shelter

and new microhabitats (Lambert *et al.*, 2023; Nordberg *et al.*, 2021; Sinha *et al.*, 2018; Uldrijan, Winkler & Vaverková, 2023). Native vegetation, insect pollinators, and birds have been shown to benefit from the increased structural complexity provided by solar panels (Beatty *et al.*, 2017; DeVault *et al.*, 2014; Visser *et al.*, 2019). Solar

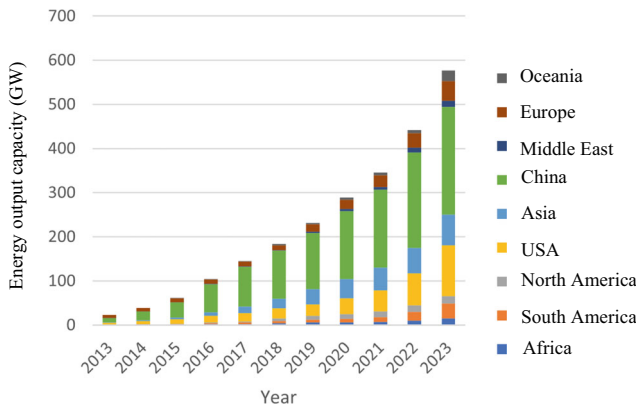


Fig. 5. Increase in solar energy output from 2013 to 2023 broken down by region. Supplementary data used for this graph can be found at the Global Solar Power Tracker, Global Energy Monitor (<https://globalenergymonitor.org>) May 2023 release ‘New Solar Capacity Added by Country and Year’ and ‘Planned Solar Capacity Additions by Country and Year’ summary tables. Countries with a significant energy output capacity (GW) in comparison with their respective continents (China and USA) are shown separately in order to showcase their role better in global solar energy output.

farms have the potential to allow a greater diversity of plant species than a field primarily used for grazing or other agricultural practices, which in turn can support a greater diversity of pollinators and other invertebrates (Carvalho *et al.*, 2023; Meyer *et al.*, 2023; Montag, Parker & Clarkson, 2016). Solar farms in Europe, in particular, provide suitable habitat for wildflowers, and the delay in bloom timing in flowers situated underneath solar panels due to greater shading benefits later-season foragers and pollinators (Blaydes *et al.*, 2021, 2022; Graham *et al.*, 2021). Additionally, the structure provided by solar farms (as well as remnant habitat features such as logs and hollows) allows pollinators such as bees to nest on site (Biesmeijer *et al.*, 2020).

Arthropod detritivores provide vital ecosystem services by recycling nutrients, and they are abundant in solar farms, especially in areas of abundant vegetation (Armstrong, Kulikowski & Philpott, 2021; Montag *et al.*, 2016). However, solar farms have the potential to affect other invertebrate species adversely. Polarotactic invertebrates are attracted to polarized light and can show reduced reproductive success on solar farm sites which can act as ecological traps (Horváth *et al.*, 2010). This can be offset by panel design alterations, greatly reducing the propensity for polarotactic insects to become attracted to them (Horváth *et al.*, 2010).

Conservoltaic systems which provide additional habitat features can help offset wildlife displacement during solar farm construction; in cases where solar farms are built on degraded landscapes, they may even facilitate environmental restoration (Cameron, Cohen & Morrison, 2012; Dhar *et al.*, 2020; Guerin, 2017; Hernandez *et al.*, 2014; Lovich & Ennen, 2011; Montag *et al.*, 2016). By contrast, the long-term

Table 3. Summary of the key benefits of agrivoltaic and conservoltaic systems.

System	Key benefits	References
Agrivoltaic	Benefits from multi-use landscape increase economic value of land	Dinesh & Pearce (2016); Dupraz <i>et al.</i> (2011); Nordberg <i>et al.</i> (2021); Valle <i>et al.</i> (2017)
	Incorporation of livestock (useful for vegetation management)	Mamun <i>et al.</i> (2022); Nordberg <i>et al.</i> (2021); Zaplata (2023)
	Incorporation of crops	Cosgun (2021); Dupraz <i>et al.</i> (2011); Ezzaeri <i>et al.</i> (2018); Graham <i>et al.</i> (2021); Marrou <i>et al.</i> (2013b)
Conservoltaic	Benefits from multi-use landscape increase economic value of land	Adeh <i>et al.</i> (2018); Moore-O’Leary <i>et al.</i> (2017); Nordberg <i>et al.</i> (2021); Peschel <i>et al.</i> (2019); Turney & Fthenakis (2011)
	Increase in local biodiversity	Armstrong <i>et al.</i> (2016); Biesmeijer <i>et al.</i> (2020); Blaydes <i>et al.</i> (2021); Meyer <i>et al.</i> (2023); Montag <i>et al.</i> (2016)
	Avian mortality not as high as in alternative renewable technologies	DeVault <i>et al.</i> (2014); Guerin (2017); McCrary <i>et al.</i> (1986); Visser <i>et al.</i> (2019); Walston <i>et al.</i> (2016)
	Vegetation reduces ambient temperature, increasing solar panel efficiency	Tsilini <i>et al.</i> (2015)
	Vegetation reduces backsheet degradation and prevents dust accumulation on solar panels	Fairbrother <i>et al.</i> (2018); Mani & Pillai (2010); Mejia <i>et al.</i> (2014)
	Provides wildlife habitat and adds structural complexity	Blaydes <i>et al.</i> (2022); Semeraro <i>et al.</i> (2018); Sinha <i>et al.</i> (2018); Tanner <i>et al.</i> (2020); Uldrijan <i>et al.</i> (2023)

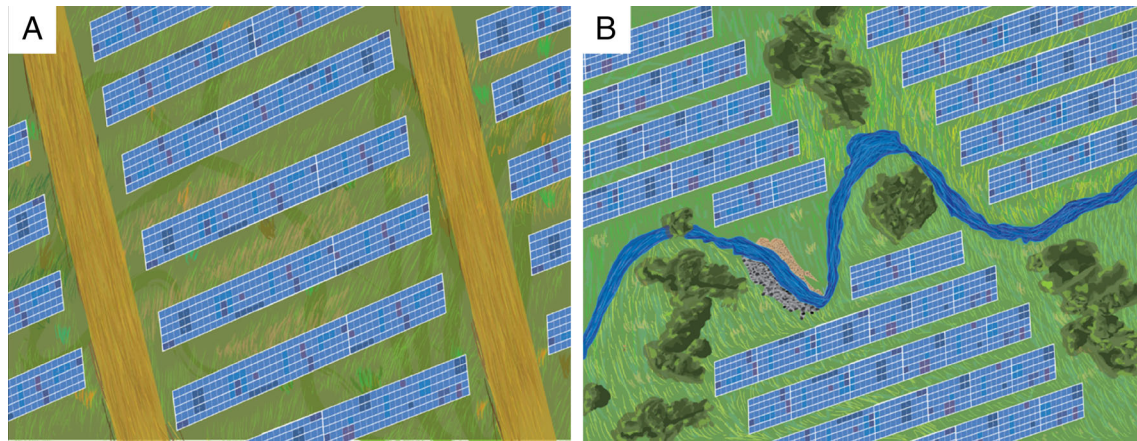


Fig. 6. (A) An example layout of a photovoltaic array used solely for solar energy development. (B) A preferred, strategic design for a conservoltaic array incorporating retained/revegetated habitat patches within the boundaries of the solar farm.

impacts of solar farm construction remain largely unknown for wildlife (Moore-O'Leary *et al.*, 2017). Rates of recolonization and the suitability of created microclimates are highly dependent on a number of factors such as climate, geography, solar farm size, and retained habitat features (Guerin, 2017; Tanner *et al.*, 2020). The planning of solar farms should take these factors into account and attempt to mitigate species displacement whilst incorporating features that benefit local wildlife (Agha *et al.*, 2020).

V. MANAGEMENT RECOMMENDATIONS

The biodiversity crisis has been exacerbated by habitat loss, degradation, and land conversion for anthropogenic uses, notably agriculture and urban sprawl. While the protection of natural habitats is of paramount importance, land-sparing and land-sharing opportunities in anthropogenic landscapes can and should be explored to increase the availability of essential habitat features and to increase habitat connectivity. The ability of human-dominated landscapes to sustain wildlife through proper planning has been well documented, and conservation can be augmented through the strategic placement of artificial habitat structures. As global energy production continues to shift towards renewable sources of energy, there is a clear opportunity to maximize land productivity *via* conservoltaic systems.

Multi-purpose uses for photovoltaic systems provide marked benefits as opposed to a single-use design. Single-purpose photovoltaic systems can produce a 'heat island' effect, raising ambient temperatures in their immediate area (Barron-Gafford *et al.*, 2016), contribute to habitat fragmentation, and minimize land productivity (Oudes, van den Brink & Stremke, 2022). Multi-purpose uses, on the other hand, increase land productivity (Toledo & Scognamiglio, 2021), provide new microclimates for wildlife to occupy (Peschel *et al.*, 2019), foster relationships between often competing

industries, and are more water efficient (Cosgun, 2021). This is true for both small and large facilities; smaller facilities can maintain habitat connectivity while larger facilities incorporating habitat patches can support viable populations (Peschel *et al.*, 2019). Thus, conservoltaic systems with multi-functionality are clearly preferable (Fig. 6).

Artificial habitat structures have been successfully implemented to enhance conservation goals in human-disturbed landscapes. The most successful iterations tailor the artificial habitat structures for particular species. Regions where significant research has been undertaken on artificial habitat structures also coincides with considerable investment in solar energy. These regions are prime candidates for the development of conservoltaic systems, most notably Australia, Canada, Spain, the UK, and the USA (Figs 3 and 4).

In the planning phase of solar farm development, environmental impact assessments and biodiversity surveys are undertaken, giving developers an understanding of the types of species and habitats present, and what measures must be taken to limit disturbance. It is in these preliminary reports where habitat features such as hollow-bearing trees, burrows, woody debris, and rock piles, and lists of native and threatened species, are identified. These species and habitat features can provide insights into which artificial habitat structures can be placed (or replaced) during the development phase to offset species dispersal during the construction phase and aid in recolonization efforts following installation, and any specifications to these artificial structures to enable the best outcome for species conservation.

VI. CONCLUSIONS

(1) Artificial habitat structures have been successfully implemented to mimic natural structures for wildlife use across the globe, often in an attempt to rehabilitate already degraded

systems, but they do not represent a long-term solution to replace natural sites.

(2) The current and predicted expansion of solar farms provides a land-sharing opportunity that allows for the energy needs of humans to be met while considering the conservation needs of wildlife.

(3) Conservoltaic systems have the greatest potential to be implemented in areas with both a significant investment in solar energy and a body of research into the effectiveness of targeted artificial habitat structures in disturbed landscapes (e.g., Australia, USA, UK, Canada, and Spain).

(4) Although research on the interactions between wildlife and solar farms has largely been restricted to Europe and North America, initial results show promise for native flora, birds and insect pollinators. However, more research is needed to understand how mammals and herpetofauna in particular interact with these structures.

(5) As solar energy is a relatively new and emerging industry, designing conservoltaic systems as solar farm construction occurs rather than when a majority of the capacity has already been built will allow better conservation outcomes, minimize displacement, and require less work than incorporating these structures retroactively.

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IX. SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. List of studies used to create the map shown in Fig. 3.

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