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A well-known tool based on unstable rock: systematic review of design, effectiveness and costs of various artificial refuges for reptile conservation

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***Abstract.*—With the loss and homogenization of natural habitats, artificial wildlife refuges are important tools. Since one of the main obstacles is the cost of construction and subsequent monitoring of their effectiveness, it is essential to optimize procedures. Preferably, the technical specifications of the refuges and an assessment of their effectiveness should be available, as well as an estimate of the total cost. Using the PRISMA method and a Google Scholar search, we reviewed publications on the construction of various types of refuges (e.g. burrows, walls) for squamate reptiles, a speciose but highly endangered zoological group. Our results show that despite the successes associated with the construction of refuges, precise technical information is often lacking. The experimental approach needed to isolate key factors (*e.g.* refuge size *versus* ability to buffer climatic variation), to guide technical improvements and to assess overall costs, is generally lacking. While the empirical and expert-based approaches are essential, the construction of refuges could be improved by following some rules, in particular by providing the technical characteristics of the refuge, the construction and labour costs, the assessment of effectiveness (including failures) and, where possible, an experimental approach.**

Keywords. Shelter, technical recommendation, habitat management, habitat restoration, squamates reptiles, PRISMA

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Introduction

The loss of natural habitats due to increasing urbanisation, intensive agriculture and infrastructure development is a major threat to terrestrial wildlife (Hanski, 2011; Newbold et al., 2016). Governments have responded with a range of measures, including the establishment of protected areas. In addition, the destruction and alteration of natural habitats is regulated by laws that attempt to limit their extent and impose obligations to restore or compensate for ecosystems altered by human activities when it is impossible to avoid impacts (Gann et al., 2019). However, the effectiveness and surface area of protected areas can still be improved, while ecosystem restoration and rewilding, despite significant successes, still face conceptual and technical challenges (Carver et al., 2021; Gann et al., 2019; Li et al., 2024; Torres et al., 2018). The effectiveness of restoration or compensation measures is often difficult to assess due to a lack of experimental approach and long-term monitoring. It is therefore important to identify operational elements that can be improved. Beyond general principles and recommendations that are central to achieving biodiversity conservation goals, smaller-scale goals provide basic elements. In this review, we consider one such basic element, the construction of refuges for squamate reptiles, which represent more than 12,000 species (Uetz et al., 2024). Reptiles are in steep decline worldwide (Böhm et al., 2013; Reading et al., 2010; Santos et al., 2022; Todd et al., 2009), and it is

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vital that we refine our approaches and techniques to help the remaining populations.

Building wildlife refuges is a widely used restoration tool for different taxa, such as birds or bats (Keppers et al., 2008; Mering and Chambers, 2014; Rueegger, 2016). Although the benefits are generally clear, all potential impacts must be considered, as artificial refuges can have negative effects. For example, they can act as ecological traps (Zhang et al., 2023). Squamates are particularly dependent on the availability of refuges. Indeed, the fact that these organisms are ectothermic has two important consequences. First, their low metabolic requirements are associated with long periods of low activity. Individuals remain hidden in buffered refuges, especially when environmental conditions are unfavourable or when it is in their interest to limit their movements, *e.g.* during digestion, moulting, wound healing, egg incubation (Bonnet & Brischoux 2019; Shin et al., 2021; Siers et al., 2018). Second, their metabolism is regulated by thermal gradients, and cool refuges are as important for thermoregulation as areas exposed to the sun (Goode et al., 2004; Regal, 1967). The same reasoning applies to moisture conditions (Chukwuka et al., 2020). Many studies have focused on the importance of refuges in reptiles, for example to cope with seasonal or daily variations in climatic conditions or to limit predation pressure (Lelièvre et al., 2010; Pearson et al., 2005; Turner et al., 2024; Whitaker and Shine, 2003).

Inspired by these findings, the construction of artificial refuges (e.g. burrows, rock or wood piles) has been successfully used to compensate for the artificialisation and homogenisation of habitats, as well as to restore degraded habitats, caused, for example, by intensive agriculture or lack of forest management (Canós-Burguete et al., 2023). They have also been widely proposed or recommended to compensate the destruction of protected species and their habitats. In particular, they have been used to promote reproduction, provide egg-laying, hibernation and aestivation sites (Arida and Bull, 2008; Bruckerhoff et al., 2021; Choquette et al., 2024; Croak et al., 2010; Gillingham and Carpenter, 1978; Grillet et al., 2010; Shine and Bonnet, 2009; Thierry et al., 2009; Whiting and Booth, 2012; Zappalorti and Reinert, 1994). In practice, however, lack of funding is one of the main barriers to ecological restoration (Cortina-Segarra et al., 2021). Measuring the costs and benefits of each element of ecological restoration is therefore central to optimising action on the ground (Choquette et al., 2024; Pike, 2016). This is particularly true for well-buffered hence large reptile refuges that are essential for reproduction (Shine and Bonnet, 2009). It is then important to estimate all construction costs, including land acquisition, materials (e.g. rock, sand, organic matter, slabs), machinery (e.g. dump trucks, excavators) and, most importantly, the manpower required to manage the project and construct the refuges (Whiting and Booth, 2012). This is in addition to the field work, and associated costs, of monitoring the environmental conditions of the refuges (e.g. temperature and humidity loggers) and the animals (e.g. mark recapture surveys and/or radio tracking), which are necessary to assess the effectiveness of the interventions. Setting aside cost considerations, long-term monitoring is rarely addressed after the creation of artificial refuges. This makes accurately assessing the value of such interventions difficult.

An experimental approach in the field is particularly useful for optimising the construction of refuges, especially large ones, which are essential for aestivation, hibernation and reproduction (Madani et al., 2023; Pike, 2016; Thierry et al., 2009). The influence of a limited number of key factors, such as refuge size or density of refuges, can then be assessed in the least ambiguous way (Hurlbert, 1984). The experimental approach is particularly recommended when the proposed construction involves significant costs, novel techniques and when it is necessary to favour certain species while limiting competing species (Deso and Reynier, 2024; Langkilde and Shine, 2004). Although various types of refuges have been tested, to our knowledge there is no review that approaches the construction from a practical and operational perspective, including costs and the experimental approach. We conducted a systematic review of the literature, focusing on: 1) the accuracy of the description of artificial refuges, taking into account the experimental approach and the assessment of their effectiveness; 2) the costs of constructing and monitoring artificial refuges. To organise the review, we considered the main taxa of target species and their life style (e.g. terrestrial, fossorial).

Materials & Methods

A systematic literature review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Moher et al., 2009). The literature was searched using Google Scholar on 19 November 2024 and 21 January 2025. This database was used for this capacity to capture grey literature (e.g. non-academic reports), a key issue in this study. As our first search with the keyword “refuge | shelter + reptile” yielded >90,000 items, mostly related to the use of natural refuges for a wide range of taxa or for bioclimatic issues, we refined our keyword selection by adding “artificial”. Only English keywords were used to cover the international literature, including non-English references. No data range was applied. Keywords and their combinations are presented in Figure 1 and Appendix 1 (e.g. “artificial refuge | artificial shelter | artificial hibernaculum + snake | reptile | lizard”). For each search, the first 100 results were retained and duplicates were removed. The bibliographic section of relevant references (e.g. Boscarino-Gaetano et al., 2024; Liberman et al., 2024; Watchorn et al., 2022) nest boxes, chainsaw hollows, artificial burrows, and artificial hibernacula have all been successfully

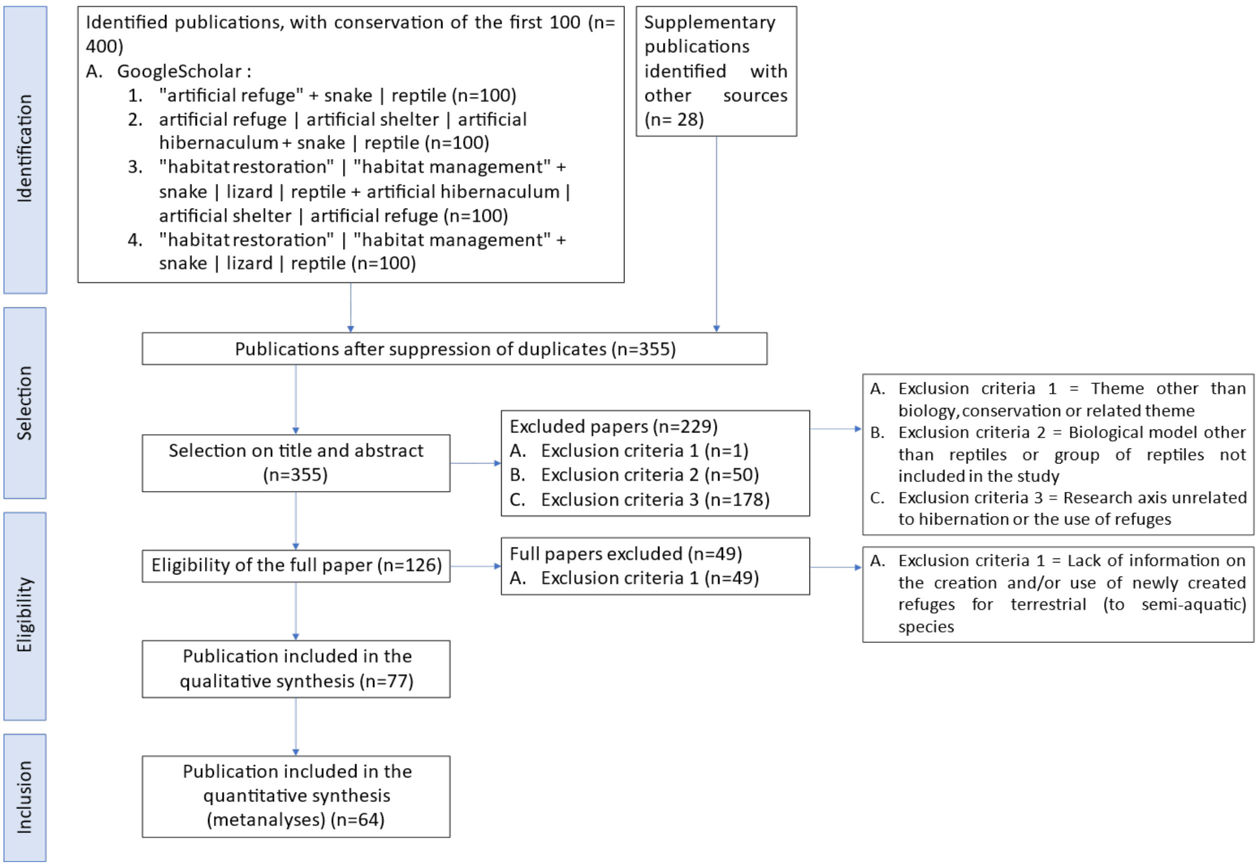

Fig. 1: Results of the PRISMA methodology.

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 and the textbook 'Reptile Ecology and Conservation' (Dodd, 2016) were examined as additional sources. Important studies or reports may have been missed. However, it is unlikely that any key studies were missed, as they would probably have been cited in the bibliographies of the recent reviews and articles we consulted.

The first selection steps allowed excluding items unrelated to conservation, biology or reptiles. Then, an important selection criterion relates to the definition of a refuge/shelter (refuge therein), which includes natural (e.g. stone), temporary (e.g. a bush) and built (e.g. abandoned buildings) refuges. Although all refuges, whether natural or constructed, are important sources of inspiration for refuge design, we have concentrated here mainly on studies that present the construction of refuges for conservation purposes. We have retained the definition of 'refuge' as a structure that protects individuals from multiple stressors over a potentially long period of time (Boon et al. 2023). We have expanded it to include other functions (e.g. digestion, resting, hibernation) and thus consider structures with thermal and hydric buffering capacity against important climatic fluctuations (Brown et al., 1974; Macartney et al., 1989). Thus, we excluded studies that relied on the use of artificial cover (e.g. slabs) or other light devices for censuses or monitoring, which offer limited buffering capacity. These lightweight artificial refuges protect individuals from predators while allowing them to thermoregulate as if exposed to the sun, thus increasing the likelihood of detecting individuals (Billy et al., 2024). However, their poor ability to buffer climatic variations means that they are unable to fulfil the role of 'deep' refuges such as burrows, crevices, large hollow trees, etc. They are avoided by reptiles during periods of extreme heat or cold, or for incubating eggs, for example. While lightweight artificial refuges can be beneficial to reptiles and may be considered as valuable enhancements in certain contexts, we did not consider the few habitat improvement studies that were too vaguely described and difficult to optimize, such as the addition of coarse woody debris (Manning et al., 2013; Palmer et al., 2022; Shoo et al., 2014). Furthermore, the use of these types of lightweight artificial refuges was the subject of a recent review in which only 12 out of 490

Table 1: Summary of the number of studies identified on the creation of artificial shelters for the conservation of reptiles. The table is organised according to major taxonomic groups and lifestyle. The sign 'X' means that the box is impossible (e.g. there is no fully aquatic gecko); the sign '?' indicates boxes for which there are doubts (e.g. some species are difficult to classify). The numbers in brackets indicate the number of species.

Taxon	Terrestrial	Semi-fossorial	Semi-arboreal	Semi-aquatic	Fossorial	Arboreal	Fully-aquatic
Gekkota (1,678)	6	0	2	0	X	0	X
Scincoidea (1,768)	13	0	0	0	?	?	X
Lacertoidea (589)	19	0	0	0	?	?	X
Serpentes (4,145)	24 (1,400)	3 (603)	0 (396)	4 (318)	0 (821)	0 (349)	0 (64)
Anguimorpha (226)	8	0	0	0	0	X	X
Iguania (1,692)	1	0	0	0	X	0	X

studies addressed reptile habitat enhancement (Liberman et al., 2024).

In the following steps, we recorded the type of literature (scientific or grey), the species (or group of species) studied, the technical information available (e.g. construction material, refuge size and density) and the occurrence of the experimental approach (Supplementary material 2 & 3). We have summarized the information in Table 1. To take into account the diversity of reptiles, we used a simplified taxonomy as an entry (Simões and Pyron 2021). We also took into account the lifestyle of the species (Fosseries et al., 2024). Impossible cells, e.g. only snakes include truly aquatic species where individuals never venture ashore, and unclear cells were indicated. The number of species for each taxon was given (Uetz et al., 2024), in addition for snakes the number of species per lifestyle was also given (Fosseries et al. 2024).

Results

PRISMA: Of the 355 articles extracted in the initial stages, the selection process resulted in a final pool of 77 items, 78% (N=60) scientific and 22% (N=17) grey literature (Figure 1, Supplementary material 1). Fifty provided guidance and prescriptions for the creation of artificial refuges (Table 1). The number of items per cell was small and many cells were empty. Even among the well-represented Serpentes suborder (comprising 4,145 species), the 31 items were limited to terrestrial, semi-fossorial, and semi-aquatic lifestyles, leaving four cells empty. The superfamily Lacertoida (19 items) was represented by terrestrial species only. The Iguania suborder was the least represented, with only one terrestrial species (*Cyclura lewisi*).

Technical characteristics of the refuges: Out of fifty items providing technical information, six types of characteristics were identified, but some information was inferred rather than clearly stated. 1) season of creation (20% of the items, N=10); 2) refuge on the ground *versus* (partially) underground (100%, N=50); 3) depth, where appropriate (55%, N=11); 4) surface of the refuge (26%, N=13); 5) materials used for construction (96%, N=48); 6) additional recommendations as exposure to sun or protection from flooding (36%, N=18).

The characteristics were also influenced by the ecological purpose of the refuges. Large refuges (>10m²) were often designed for hibernation or aestivation, they represented 52% (N=26) of the items. Other refuges were designed to meet specific needs, such as dependence on saxicolous or fossorial habits; these included flat stones and/or slabs (18%, N=9) or galleries and underground chambers (16%, N=8). Alternative design was designed for specific approaches and species, mostly within lab conditions (14%, N=7).

Monitoring: Colonization and occupation have been assessed within 32 studies (64%) using presence/absence monitoring (69%, N=22), capture-mark-recapture (CMR) (25%; N=8) and radio tracking (6%, N=2). Installing tubes throughout the refuge allowed monitoring of the occupancy of the central cavity (2%, N=1) and monitoring temperature and humidity (8%, N=4). Monitoring was typically limited to the colonization of artificial refuges by a target species, with record of natural colonisation and use (87%, N=28), but has rarely been designed to assess population or community consequences (Grillet et al. 2010; Croak et al., 2013; Davis and Theimer, 2003; Madani et al., 2023).

Costs: six items (12%) provided construction costs and 1 item (2%) labour costs.

Experimental approach: 12 items were based on experiments, 8 in the field and 4 in captivity. The studies in question tested several factors: type of refuge (92%, N=11), difference between habitats (17%, N=2), preference between natural and artificial refuges (17%, N=2), interaction of artificial refuge with environmental factors (8%, N=1) and predator control (8%, N=1). Most were conducted on small lizards (83%, N=10). Comparisons of these parameters were made between artificial and natural refuges understand their impact (Ebrahimi et al., 2012).

Comprehensive information: one reference provided detailed comprehensive information for overwintering refuges, including all costs (Choquette et al., 2024); although the experimental approach was not undertaken.

Discussion

The creation of artificial refuges may not be necessary for species that are entirely pelagic (e.g. *Hydrophis platurus*), arboreal (e.g. *Corallus* sp.) or sand-dwelling (e.g. *Eryx jayakari*). This probably explains the blank cells in Table 1 that correspond to specific lifestyles. In these cases, other conservation measures could be proposed, such as habitat restoration or protection. The possible role of other types of refuges for truly marine non-pelagic species (e.g., artificial reef wrecks for marine snakes such as *Aipysurus laevis*), has not been well documented and remains questionable. For most species, however, the creation of refuges (including lightweight) is likely to have a positive effect. The case of grass snake (*Natrix natrix*) populations in Sweden illustrates the importance of artificial structures. The abandonment of traditional farming practices has led to a drastic reduction in the number of manure heaps, resulting in a decline in the number of snakes, which no longer have egg-laying sites (Löwenborg et al., 2012). However, while numerous studies have demonstrated the importance of natural or artificial refuges for squamates, the benefits of constructing artificial refuges have only been documented for a small number of species. Furthermore, there are gaps across species and lifestyles. For example, only one case has been found for the Iguania group, which includes around 1700 species. The groups most represented in this review are those that are most widely studied in general, resulting in a bias toward species from temperate zones.

It should be useful to list the main benefits of natural or artificial refuges, but this step is barely present (Boscarino-Gaetano et al., 2024; Cowan et al., 2021). Monitoring of new artificial refuge is scarce among reviewed literature, with only few references presenting relevant surveys to assess their true effect (e.g. using CMR or radio tracking). Studies have documented positive outcomes such as the use of artificial hibernation or breeding sites by snakes and lizards (Gillingham and Carpenter, 1978; Shin et al., 2021; Zappalorti and Reinert, 1994). Artificial refuges can contribute to population maintenance, particularly by improving survival or recruitment (Croak et al., 2010, 2013; Grillet et al., 2010; Bruckerhoff et al., 2021; Davis and Theimer, 2003). However, most interventions have not been monitored long enough (e.g. only part of the year or of species cycle) to ascertain benefits. In addition, the lack of studies reporting failures limits the ability to avoid unnecessary construction or errors. Without this knowledge, it is difficult to guide regulatory requirements or propose truly relevant projects. While it is important to use field studies as a basis for habitat improvement or restoration, and to better understand the causes and pressures on species, systematic approach to shelter construction has the potential to improve the conservation toolbox. This could also help to determine whether and to what extent shelter deficit is a real limiting factor. Broad or empirical approaches have their limitations, particularly when there are gaps in the precise technical description of refuge construction. This review therefore emphasizes on the technical data needed by decision-makers, managers and conservationists who have to make decisions. Some of the limitations are discussed below.

Among squamates, there is considerable geographical variation among populations, including in habitat use, and therefore potentially in refuge types (Chandler et al., 2022). This variability may limit the transferability of artificial refuges. For example, refuge boxes buried in the sand and connected to the outside by calibrated plastic pipes are excellent refuges for the ocellated lizard (*Timon lepidus*) in the Atlantic dunes, but not necessarily in the Mediterranean limestone scrublands where most populations are found (Grillet et al., 2010). Ecological differences between closely related species should also be taken into account. Natural or artificial free beach-rocks located in a specific intertidal zone are essential refuges for blue sea-kraits (*Laticauda laticauda*) but not for yellow sea-kraits that are capable of using a wide variety of refuges (*L. saintgironsi*) (Bonnet et al., 2009). These two species, which use the same coral islands, will respond differently to conservation actions based on a single type of artificial refuges (Bonnet & Brischoux 2019). This means that even the filled-in cells in Table 1 may be more incomplete than initially estimated.

Large, partially enclosed refuges should have a strong capacity to buffer ambient thermal and hydric fluctuations (McKelvey, 2024) and they are likely to be suitable for many species to meet their key ecological needs (hibernation, aestivation, reproduction, etc.). However, given systematically limited financial resources, it is essential to optimise the size, depth, number and density of artificial refuges among other things. Yet, important information is often lacking, such as the depth of the excavation or the volume of the refuge. This last parameter, which is generally neglected, may be important in certain biotopes subject to extreme climatic conditions (e.g. arid desert) where too great a distance between refuges may even prohibit movement (Lagarde et al., 2012). Having access to accurate and relevant information can help prevent the random selection of construction parameters, which could result in unnecessary costs (oversizing) and/or poor shelter quality (undersizing). Similarly, monitoring of thermal and moisture conditions of refuges, as well as occupancy by target species, is not systematically reported. Even rarer are studies that consider all the elements useful to managers (Cowan et al., 2020; Watchorn et al., 2022). In addition, artificial refuges should be compared with natural refuges and occupancy assessments should preferably be carried out over the long term (Ebrahimi et al., 2012; Herbert, 2020).

One important factor is that construction and monitoring costs are generally not considered in the scientific literature, perhaps because these costs are covered by research programmes (Deso and Reynier, 2024; Tatin and Renet, 2016). This practical knowledge is more commonly found in the grey literature. Although not peer-reviewed, this type of literature can be very useful for practical questions. In any case, it is important for conservation stakeholders to be informed of all costs, both in terms of material and labour, in order to make the necessary trade-offs between costs and the researched positive effects of the measure.

It is not always possible to set up experiments in the field, but part of the lack of experimental results is due to initial choices: it is essential to carry out experimental tests to find the best solution in order to implement appropriate conservation measures in relation to the ecology of the target species (Figure 2). If several refuges are planned, it is desirable to vary one (or a few) key factors (Staugas et al., 2013; Thierry et al., 2009). Additionally, those findings might provide guidance to avoid negative impact and the creation of ecological traps. Even though failure was not documented in the compiled literature, the need to pursue experimentation to obtain more efficient artificial refuges was recognized (Tatin and Renet, 2016; Turner et al., 2024).

Conclusion

Despite relevant findings (Table 1), from an operational point of view, the taxonomic and ecological diversity of squamates and their specific needs do not fit well with the small number of studies on artificial refuges. Large refuges made of heterogeneous materials can accommodate different species, different age cohorts and fulfil different ecological needs; they play a generalist role. However, refuges that are precisely sized, positioned and constructed with selected materials, often targeted at species or populations at risk of extinction, also have a role to play (*e.g.* conservation of New Zealand lizards). In all cases, it is essential to optimise the construction, but on what basis? Taking into account the environmental, logistical and financial constraints on the construction of reptile refuges, this review highlights some major shortcomings. In order to standardise techniques, we suggest that the designs be described in detail, including the costs, and that an experimental approach be taken where possible. An important point is to assess the need for the construction of refuges, and if so, to carefully select the locations. Indeed, the benefits for target species and associated habitats are rarely documented. As many studies have not been subject to quantitative follow-up or control comparisons, our ability to assess the true impact of conservation is limited. There may also be a publication bias in favour of successful cases. Thus, while compiling what is known, we emphasize that the effectiveness of most interventions has yet to be critically evaluated. Filling these gaps is an urgent challenge for conservationists as they try to find the best way to ensure the restoration of suitable habitats for target taxa, and to avoid the creation of ecological traps.

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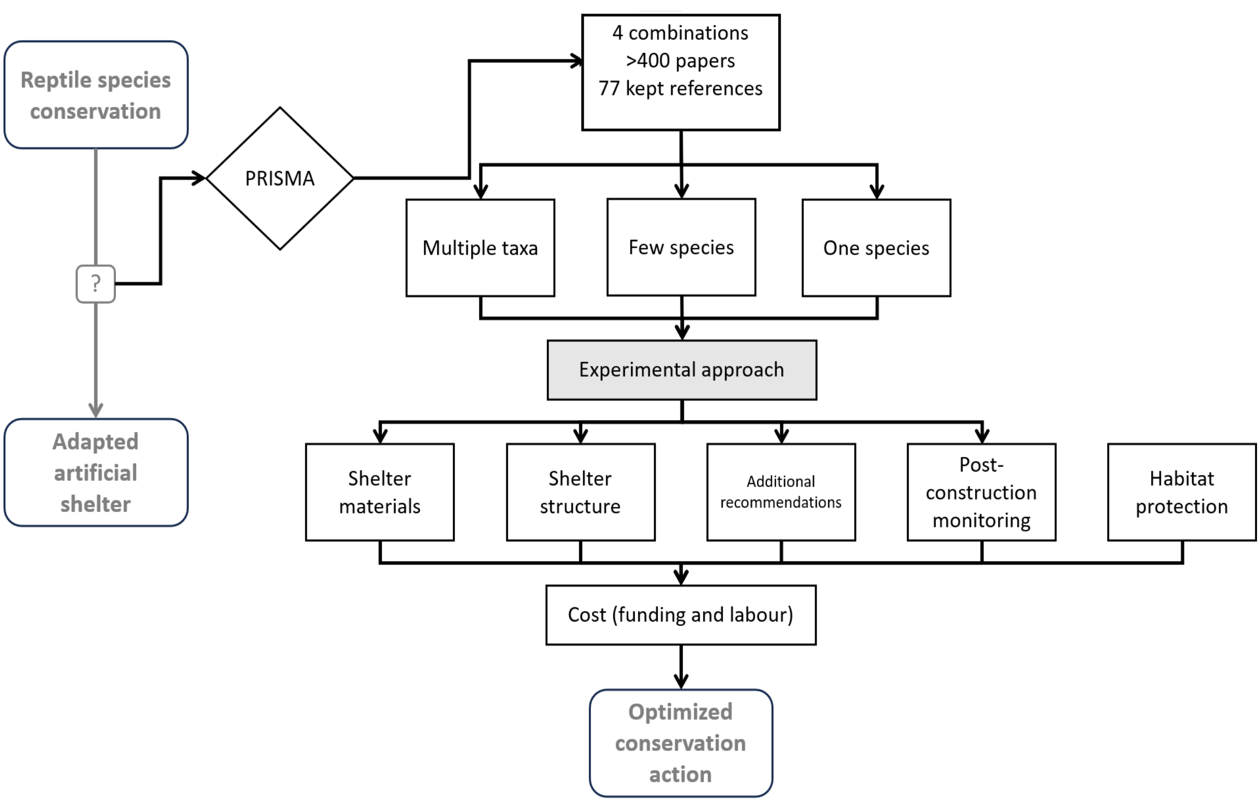

Fig. 2: Organization chart of relevant approach to achieve an optimized conservation action.

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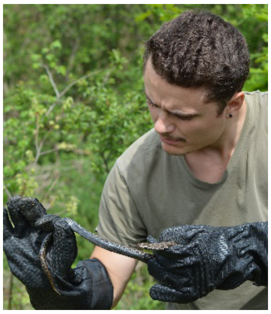

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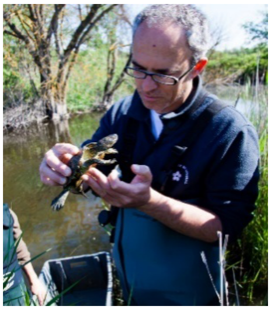

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Appendix 1. Terms, associated number of results and conserved publications. +: "and"; |: "or".

Terms used	Number of results	Conserved publications
artificial refuge + snake | reptile	45900	100
artificial refuge | artificial shelter | artificial hibernaculum + snake | reptile | lizard	1750	100
"habitat restoration" | "habitat management" + snake | lizard | reptile + artificial hibernaculum | artificial shelter | artificial refuge	4810	100
"habitat restoration" | "habitat management" + snake | lizard | reptile	16800	100

Appendix 2. Technical characteristics of artificial shelters.

Reference	Type of literature	Experimental test	Target group (species)	Period of creation	Bottom dug		Surface	Composition	Other preconisation
					Yes/No	Depth			
Shelters and hibernacula									
ARCA2E, 2023	Grey	No	Reptiles	Late summer to early fall	Yes	0,50m	/	Bottom: thin layer of sand, gravel or uncompacted soil. General: mixture of large blocks, branches, tree stumps and crushed vegetation. Top: layer of pebbles or a few rocks and uncompacted soil.	/
Casanova, 2022	Grey	No	Reptiles	/	No	/	/	Bottom: / General: mix of tree trunks, large stones, branches, brush, boards, leaves, bricks and uncompacted soil. Top: mix of brush, uncompacted soil and leaves.	High point. Good exposure. Connectivity with the existing environment (edge, rypisilve).
Deso and Bonnet, 2024a, 2024b	Scientific	No	Snakes	/	Yes	/	> 20m²	/	/
Deso and Reynier, 2024	Scientific	No	Geckos (*Euleptes europae*)	September	No	/	**±10m²**	Bottom: / General: concrete blocs (50 x 25 x 20 cm) on three layers, with 0.4-0.7 cm spaces between blocs. Top: uncompacted soil.	/
GéoPlusEnvironnement, 2013	Grey	No	Reptiles	/	Yes	2m	/	Bottom: / General: large stones, concrete blocks, stumps, piles of branches, logs, pipes (concrete); add of sand. Top: seeded uncompacted soil and scree.	Good exposure. Connectivity with the existing environment (wood).
Guérineau and Brepson, 2017	Grey	No	Reptiles	/	Yes	/	/	Bottom: / General: hollow bricks cover with flat rocks and geotextile cloth. A stone wall is constructed above and surrounding the structure. Top: uncompacted soil covered by slate slabs.	Good exposure.
Ingerop, 2022, 2023	Grey	No	Reptiles	Fall	Yes	0.50m	1-2m²	Bottom: / General: stones (5-15 cm), branches. Top: topsoil.	/
Kenwright, 2024	Grey	No	Reptiles	/	No	/	/	Bottom: / General: piles cut brambles and brackens. Top: /	/
Kerroux, 2023; Schwartz, 2020	Scientific	Yes No	Lizards (*Timon Lepidus*)	/	Yes No	/	/	Permanent shelter: Bottom: little rocks. General: half side uncompacted soil, half side limestone blocks. Top: / **« Day » refuges:** Bottom: / General: stone blocks of various sizes. Top: /	Electrical conduit (diameter of 70cm) used for temperature and humidity monitoring.
McKelvey, 2024	Scientific	No	Snakes	Spring	Yes	1-6m	150/ 262m²	Bottom: / General: large stones (0.3-0.75 cm) cover by geotextile cloth. Top: 2.5-3m of uncompacted soil to recreate the natural slope.	Presence of PVC tube for temperature and humidity monitoring.
Mouflette, Reymann, et al., 2021; Mouflette, Urge, et al., 2021	Grey	No	Reptiles	/	No	/	/	Bottom: / General: box (concrete) surrounded by litter; mixture of crushed vegetation, stumps, stones. Top: branches; stone blocks.	High point. Good exposure. Connectivity with the existing environment (edges).
Nickels & Biagi, 2015	Grey	No	Snakes	September - October	Yes	/	/	Bottom: landscape fabric. General: stones of varying sizes or logs. Top: seeded uncompacted soil.	Presence of a PVC tube for occupancy monitoring.
Reynier Environnement, 2020	Grey	No	Reptiles	/	No	/	/	Bottom: / General: Stone blocks of different sizes. Top: /	Good exposure.

Appendix 2 (continued). Technical characteristics of artificial shelters.

Seleck et al., 2022	Grey	No	Reptiles	/	Yes No	/	/	Hibernacula: Bottom: / General: stone blocks of various sizes (20-40cm). Top: uncompacted soil. **« Day » refuges:** Bottom: / General: stone blocks of various sizes. Top: /	/
Showler et al., 2005	Scientific	No	Lizard (*Zootoca vivipara*)	September	Yes	1m	30m²	Bottom: / General: plastic piping with extremity reaching the surface, cover with a mix of bricks, gravel, rubbles and vegetation. Above: logs and branches, complete by slabs and partially cover with vegetation and uncompacted soil.	South exposure. Plastic pipes are used to create entrance, entrance being reduce in size to avoid predation.
Stebbings, 2000	Scientific	No	Reptiles	/	Yes	1m	20m²	Bottom: / General: concrete blocks and crushed vegetation. Above: branches and grass cuttings.	PVC tube to create entrances.
Tatin and Renet, 2016	Scientific	No	Lizards (*Timon Lepidus*)	Winter	No	/	4m²	Bottom: / General: concrete block cover with uncompacted soil limestone blocks. Top: /	Electrical conduit (diameter of 70cm) to create entrances, used for temperature and humidity monitoring.
Vakuo, 2024	Grey	No	Reptiles	/	Yes	/	/	Bottom: / General: box (concrete) surrounded by litter. Top: branches.	High point. Good exposure. Connectivity with the existing environment (edges).
Whiting & Booth, 2012	Scientific	No	Snake (*Vipera berus*)	/	Yes	/	/	Bottom: straw. General: branches, logs, bundles of reeds. Top: uncompacted soil and peat.	Good exposure. Protected from flooding.
Zappalorti and Reinert, 1994; Zappalorti, 2016; Zappalorti et al., 2014	Scientific	No	Snakes	/	Yes	1.8m	**±18m²**	Bottom: / General: alternate stacking of railroad ties to create a rectangular box-like buried structure, fill with stumps, piles of branches, logs and sandy soil; dig part cover with railroad ties, covered with plastic sheeting. Top: stumps, branches, logs covered with sandy soil	Presence of PVC tube to create entrances.
Artificial burrows									
Choquette et al., 2024	Scientific	No	Snakes	/	No	/	/	Bottom: / General: vertical cylinder of ±160 cm long by ±10 cm wide, composed of tubes and chambers of various sizes. Top: remaining sol from excavation place surrounding the entrance.	/
Davis and Theimer, 2003	Scientific	Yes	Lizard (*Holbrookia maculata*)	August	No	/	/	Bottom: / General: handmade burrows with a 20 cm wide entrance and 60-75 cm deep. Top: /	/
Ebrahimi et al., 2012; Milne et al., 2003; Souter et al., 2004	Scientific	Yes No	Lizard (*Tiliqua adelaidensis*)	/	No	/	/	Bottom: / General: vertical cylinder of wood of 30 cm length and a 13/17/20 mm internal diameter. Top: /	/
Grillet et al., 2010	Scientific	No	Lizard (*Timon Lepidus*)	November	Yes	40-50 cm	/	Bottom: / General: wooden box of 50 x 25 x 25 cm, without bottom, laterally connected to the surface using two PVC ringed pipes. Top: sand.	/
Madani et al., 2023	Scientific	Yes	Skink and snakes	/	No	/	/	Bottom: / General: vertical cylinder of ±14 cm long by ±2 cm wide. Comparison with roof tile (329 mm wide and 415 mm long, 25 mm thick). Top: /	/

Appendix 2 (continued). Technical characteristics of artificial shelters.

Staugas et al., 2013	Scientific	Yes	Lizard (*Tiliqua adelaidensis*)	/	No	/	/	Bottom: / General: 1) vertical cylinder of wood of 20 cm long and a 20 mm internal diameter; 2) 10cm long cylinder with a basal chamber of 100 mm diameter; 3) 15cm long cylinder with a basal chamber of 60 mm wide for 50 mm depth; 4) 16 cm long cylinder with a basal chamber of 40 mm wide for 40 mm depth. Top: sand.	/
Specific structures									
Agnew, 2022	Scientific	No	Skinks and other small lizards	/	No	/	/	Habitat Pods consisting of an exterior perforated cardboard shell supported by an internal base.	Placed in order to create networks.
Burton, 2010	Scientific	No	Monitor lizards (*Cyclura lewisi*)	/	No	/	/	Yearlings retreats: Concrete structure reproducing hollowed branches, installed in trees. Adults retreats: Concrete structure with loop configuration, cover with rocks and installed on the ground.	/
Croak et al., 2010, 2012, 2013	Scientific	No	Reptiles	/	No	/	/	Artificial rocks of ±55 x 38.5 cm, with a mean thickness of 42 mm; strips of closed-cell foam tape (1.5 cm wide and 1 cm thick) present at the bottom to create a frame with 0.4-0.6 cm interstices.	/
Gillingham and Carpenter, 1978	Scientific	No	Snakes	/	Yes	1.9m	**±43m²**	Bottom: layer of poured concrete with drain and run-off sink. General: walls made of corrugated, preformed concrete building sheets; a face is covered with a concrete block stack, link to the outside at the top with a 10 cm concrete entrance. Top: seeded uncompacted soil.	Presence of an observation chamber separate by a wall and pierced by observation ports.
Cecilia Hernández-Bocardo et al., 2019	Scientific	Yes	Lizard (*Gerrhonotus parvus*)	/	No	/	/	Refuge (20 cm long × 12 cm wide × 3.5 cm high) with circular and square chamber connected by passage, on platform of 10 or 19 cm height	/
Langkilde and Shine, 2004	Scientific	No	Skink	/	No	/	/	Plastic shelter of 13 cm long x 13 cm wide x 2 cm deep.	/
Lazcano et al., 2020	Scientific	Yes	Lizard (*Gerrhonotus parvus*)	/	No	/	/	Refuge (20 cm long × 12 cm wide × 4.5 cm high) on platform of 10 or 19 cm height	/
Lettink et al., 2008; Lettink and Cree, 2007	Scientific	Yes	Skinks	/	No	/	/	Comparison of triple-layered onduline stack of three slabs (40 cm long x 28 cm wide, with 0.2 cm of space between slabs), triple-layered corrugated iron stack of three slabs (45 x2 3cm) and with one concrete roofing tile (39 × 32 cm).	/
Lettink et al., 2010	Scientific	Yes	Skink (*Oligosoma maccani*)	/	No	/	/	Comparison of single layer slabs (58 long x40 wide) with double layer slabs (40x28, with 1cm space between slabs).	/
Thierry et al., 2009	Scientific	Yes	Skink and gecko	/	No	/	/	Comparison of tree layers of undulate slabs (40 long x28 wide x 0.25 thick cm), iron slabs (45x23x0.1 cm) and solid concrete (39x32x2.5 cm).	/
Todd et al., 2009	Scientific	No	Snake (*Thamnophis Sauritus*)	/	No	/	/	Experimental hibernacula of 60 cm high, 40 cm wide and 12 cm deep, with four alternatively placed shelves (angle of ±77° from vertical) to create a zigzag. Slate aggregates are present at the bottom and on each shelf. Tubes at two levels to create a water flow.	/
Turner et al., 2024	Scientific	No	Lizards	September	No	/	/	Concrete block of 120 mm high, 320 mm long and 300 mm wide, with 5-10mm high for 230 mm wide x 250 deep crevice and a basking place in front of it.	/
Webb and Shine, 2000	Scientific	No	Skink and snakes	/	No	/	/	Artificial rocks of ±19 cm wide x 5 cm thick, creating tow size of interstices with the ground of 4 and 8mm.	/

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Appendix 3: Proposed guidance to report information during shelter construction

Period of creation:

Construction should be preferably carried out during period of low or declining activity. However, the possibility of individuals escaping during construction should be taken into account, for example by avoiding periods that are too cold. The periods from late summer to early autumn, with the exception of winter, should be preferred in temperate regions (ARCA2E, 2023; Deso and Reynier, 2024; Grillet et al., 2010; Ingerop, 2023, 2022; Nickels and Biagi, 2015; Showler et al., 2005).

Construction costs:

The available references suggest global costs ranging from around 70€ (60£, Showler et al., 2005) to 550€ (Ingerop, 2023, 2022), making the decision difficult for managers and stakeholders. Therefore, in addition to building materials, comprehensive information should be considered and reported. This notably includes land acquisition, equipment rental, labour, design, monitoring.

Depth of artificial refuges:

Most shelters designed for squamate reptiles are partially or fully buried to buffer environmental fluctuations. Some depths have been tested (0.5m: ARCA2E, 2023; Ingerop, 2023, 2022; 1m: Showler et al., 2005; Stebbings, 2000; 1.8m: Zappalorti and Reinert, 1994; 6m: However, in the majority of cases (most species and most situations) precise depths are not available. Different depths should be tested and the results systematically reported.

Dimensions of artificial refuges:

Few studies provide this information (e.g. 1-2m², Ingerop, 2023, 2022). The proposal to create large refuges to create different cavities are sometimes mentioned, but often without details (Deso and Bonnet, 2024a, 2024b; Deso and Reynier, 2024; McKelvey, 2024; Showler et al., 2005; Stebbings, 2000; Whiting and Booth, 2012; Zappalorti and Reinert, 1994, 1994; Zappalorti, 2016). The buffering capacity of artificial refuges against low and high ambient temperatures (or humidity conditions) should be tested and reported (Shine and Bonnet 2009).

Construction materials and technique:

- The bottom of artificial refuges aims to stabilise the refuge, particularly through the use of sand, gravel or uncompact soil (ARCA2E, 2023), small rocks (Kerroux, 2023; Schwartz, 2020), landscape fabric (Nickels and Biagi, 2015) or even straw (Whiting and Booth, 2012).
- The most common materials used to construct the core of the shelters are a mixture of stone blocks of various sizes (medium [20-40cm] to large [>40cm]), branches, tree stumps and crushed vegetation, to which construction materials (bricks, concrete structures) may be added to create cavities. Some shelter materials are more concise, with concrete structures surrounded by crushed vegetation or litter (Mouflette et al., 2021a, 2021b; Vakuo, 2024), or even limited to piles of cut vegetation (Kenwright, 2024).
- Cover: The top layer is generally uncompact or sandy soil, a mixture of organic matter or branches, possibly supplemented by stones to create hiding and thermoregulation sites. Experiments conducted for the conservation of the ocellated lizard have shown that an excessive top layer can impede passage and be detrimental (Schwartz, 2020). Buried concrete structures accessible by pipes can be effective (Kerroux, 2023).
- Burrows: Recommendations vary widely depending on the target species. They range from wooden cylinders a few tens of centimetres long and a few centimetres in diameter (Ebrahimi et al., 2012; Souter et al., 2004) to larger burrows 60-75 cm deep and 20 cm wide (Davis and Theimer, 2003). For snakes, large vertical cylinders approximately 160 cm long and 10 cm wide with chambers of varying sizes have been constructed (Choquette et al., 2024). Buried wooden boxes connected to the surface by plastic pipes work well for one species of lizard (Timon lepidus; Grillet et al., 2010). Staugas et al. (2013) tested medium-sized vertical cylinders with basal chambers of different sizes for an Australian lizard species (Tiliqua adelaidensis).
- Others: flooding must be considered, for example, by providing emergency exits or rooms with air pockets (Casanova, 2022; Edgar and Bird, 2005; Markle et al., 2020; Mouflette et al., 2021a, 2021b; Vakuo, 2024; Whiting and Booth, 2012). Providing suitable structures to promote thermoregulation can be useful (Casanova, 2022; GéoPlusEnvironnement, 2013; Mouflette et al., 2021a, 2021b; Reynier Environnement, 2020; Showler et al., 2005; Vakuo, 2024). Connectivity with the surrounding habitats is important (Lecq et al., 2018, 2017; Casanova, 2022; Cathrine and Norris, 2015; GéoPlusEnvironnement, 2013; Mouflette et al., 2021a, 2021b; Vakuo, 2024).

Overall, the diversity of the options creates a high level of complexity. It is therefore important to systematically report on all the elements involved in the construction of the shelters. The parameters could usefully be summarised in a table.

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