



Review Paper

Evaluation of the application of methods used to detect and monitor selected mammalian taxa to pangolin monitoring

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ABSTRACT

Standardised methods to monitor populations of many species are lacking but are important for detecting presence, changes in populations and species status, and for conservation management. Pangolins (Family: Manidae), are one such group of mammals that are native to Africa and Asia. Here, we conduct a systematic review of methods used to detect and monitor populations of species ecologically similar to pangolins to inform the development of pangolin monitoring methods. The primary question of this review is: how effective have methods been at detecting and monitoring populations of species ecologically similar to pangolins? We also investigated their applicability to each species of pangolin, considering the lessons learnt from the identified studies. Of the 379 articles identified by Web of Science, 159 were included, and supplemented with 87 studies from Google Scholar searches. In total, across all studies and 24 taxonomic groups, 28 different survey methods were used to detect and/or monitor the selected taxa. Based on this review, several methods have potential application to the different pangolin species. Camera-trapping may be useful for monitoring all species of pangolin, including the arboreal species. Burrow counts could be used to monitor fossorial pangolins, but there are several challenges to using this method including correct identification of burrows and identifying the ways in which pangolins use burrows/dens.

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1. Introduction

Standardised methods to monitor populations of many species are lacking, but are important for detecting changes in populations, determining species status, and for informing conservation management (Thompson, 2004). Pangolins (Family: Manidae), are one such group of mammals, and are distributed in sub-Saharan Africa and large parts of Asia (Gaubert, 2011).

Pangolins are threatened by overhunting and wildlife trafficking across their distribution, driven by local and international demand for their meat and scales (Challender and Waterman, 2017; Ingram et al. 2018, 2019; Mambeya et al., 2018). At least one pangolin species is also threatened by the placement of electric fences (largely around game reserves and national parks, Pietersen et al., 2014a), and all could be indirectly threatened by habitat destruction and degradation (Waterman et al., 2014). However, some species appear able to adapt to modified and degraded habitats (e.g. Sunda pangolin *Manis javanica*,

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Philippine pangolin *M. culionensis* (Marler, 2016), and Chinese pangolin *M. pentadactyla* (Sun et al., 2019)). All species of pangolin are listed as threatened on the IUCN Red List of Threatened Species (IUCN, 2018).

Despite all species of pangolin being threatened, robust methods of detecting and monitoring populations are lacking, hampering conservation efforts. If possible, standardised and robust methods should be sought to aid conservation practitioners in assessing the status of pangolins, monitoring population trends, and evaluating success of rehabilitation and release, to inform management interventions. Pangolins are particularly difficult to monitor for several reasons. First, they are principally nocturnal, though most species including Temminck's ground pangolin, *Smutsia temminckii* (Pietersen et al., 2014b), and Sunda pangolin (Lim and Ng, 2008), have been observed as active during the day. An exception is the black-bellied pangolin *Phataginus tetradactyla* which is diurnal/nocturnal (Kingdon et al., 2013). Second, pangolins are solitary and multiple species occur at naturally low densities (e.g. Temminck's ground pangolin in open habitats, Pietersen et al., 2014b). Third, detection is difficult because some species of pangolin use or excavate burrows in the ground (hereafter 'fossorial'), whilst others are semi-arboreal/arboreal and nest in tree cavities or under rocks, and the use of these structures by pangolins may differ by season (Lin, 2011). The white-bellied pangolin, *P. tricuspis*, and the Sunda pangolin, are semi-arboreal and can be found on the ground, in trees, and in tree cavities (Akpona et al., 2008; Wirdateti and Semiadi, 2013); and in the case of Sunda pangolin, found sleeping in clumps of tall grass (Lim and Ng, 2008). Additionally, *M. javanica*, is known to use dens in low-level cavities in tree root systems (Lim and Ng, 2008), which further decreases detectability. Temminck's ground pangolin is known to use aardvark *Orycteropus afer* burrows up to ~90% of the time, and rarely excavates its own burrows (Pietersen et al., 2014b). The Indian pangolin, *Manis crassicaudata*, is known to create 'false walls' inside burrows to minimise detection by predators (Nowak, 1999). Fourth, the average adult body mass of pangolins spans 1.5–33 kg, depending on the species (Table 1), therefore detectability differs between species and methods may not be transferable between species. Finally, pangolins occur in a variety of habitats across their ranges, even within the same species (e.g., Indian pangolin is found in close to arid areas in Pakistan and tropical forests in Sri Lanka; Mahmood et al., 2014), and some habitats may be difficult to access e.g. some dense tropical forests and seasonally flooded forests. It is therefore unlikely that one method alone will be suitable for monitoring pangolin species across the range of habitats they occupy. Despite the difficulties in monitoring pangolins, a number of methods have been used at various scales such as nocturnal surveys (e.g. Dorji, 2015), burrow counts (e.g. Akrim et al., 2017), camera trapping (e.g. Bruce et al., 2018), and community interviews (e.g. Godwill et al., 2017). Current methods have rarely been successful (Newton et al., 2008) and have been reviewed in detail in Willcox et al. (2019). Major difficulties include detecting pangolins that occur at very low densities and finding and identifying pangolin signs.

Although the literature on best practices to monitor pangolins is largely undeveloped, it might be possible to gain insights on potentially applicable methods from studies that have monitored species that are similarly difficult to monitor, but that have received greater research attention. Such studies could not only provide descriptions of the methods used, but also provide valuable insights and lessons learned.

Here, we conduct a systematic review of methods used to detect and monitor populations of species ecologically similar to pangolins to inform the development of monitoring methods for pangolins. The primary question of this review is: how effective have methods been at detecting and monitoring populations of species ecologically similar to pangolins? Secondary questions investigated are: which methods may be most appropriate for monitoring the different species of pangolins? What lessons can be learned from the methods used? What, if any, further information is needed to inform method design? It is hoped that this review will also be useful for other taxa (i.e. beyond pangolins), where monitoring methods and protocols have not yet been established e.g., Tubulidentata (aardvarks), Hyracoidea (hyraxes), and Afrosoricida (tenrecs).

2. Methods

To review the methods used to detect and monitor populations of species that are ecologically similar to pangolins, we surveyed the scientific literature using a systematic approach following Pullin and Stewart (2006). We chose this method

Table 1

Adult body mass and adaptations of the eight species of pangolin, ordered by body mass. Activity patterns: N = Nocturnal; D = Diurnal. Locomotor categories: A = Arboreal; F = Fossorial; S = Semi-arboreal. Primary diet: M = Myrmecophagous. Sociality: S = Solitary.

Scientific name	English name	Activity pattern ^a	Locomotor category ^a	Primary diet ^b	Sociality ^c	Body mass (kg) ^d
<i>Phataginus tricuspis</i>	White-bellied pangolin	N	A, F, S	M	S	1.54
<i>Phataginus tetradactyla</i>	Black-bellied pangolin	D, N	A	M	S	2.09
<i>Manis pentadactyla</i>	Chinese pangolin	N	F	M	S	3.64
<i>Manis culionensis</i>	Philippine pangolin	N	A, F, S	M	S	4.54
<i>Manis javanica</i>	Sunda pangolin	N	A, F, S	M	S	4.54
<i>Smutsia temminckii</i>	Temminck's ground pangolin	N	F	M	S	9.59
<i>Manis crassicaudata</i>	Indian pangolin	N	F	M	S	11.96
<i>Smutsia gigantea</i>	Giant pangolin	N	F	M	S	33.00

^a Added from information from the IUCN SSC Pangolin Specialist Group.

^b Although black-bellied pangolin and Sunda pangolin have been reported eating sweat bee nests and bee larvae respectively.

^c Although we note the lack of evidence on this life history trait.

^d Global average adult body mass from Myhrvold et al. (2015). Although note that this is likely to be taken from few individuals and may vary across an exploitation gradient.

because it is known to be both more extensive and repeatable, and less biased, than standard reviews (Roberts et al., 2006). For example, using a systematic search strategy reduces the likelihood of publication bias because it is more likely to pick up grey literature and studies where results are not necessarily significant (Roberts et al., 2006). However, we acknowledge that all literature may be biased towards monitoring methods that worked, rather than those that did not.

2.1. Identification of ecologically similar species

We included ecological characteristics that we considered important for monitoring pangolins and that may influence the methods used to detect and monitor pangolin populations. Ecological characteristics we included were 1) the time of day or night in which the species was active or 'activity pattern', 2) the modality of locomotion or 'locomotor category', 3) whether part of the species' diet consisted of ants or termites ('myrmecophagous'), 4) whether the species was solitary (to select for survey methods not specifically designed to detect groups of animals), and 5) body mass. The species we selected inhabit a wide geographic range to match the variety of habitats in which different species of pangolins live. We also specifically included research on species that live outside the range of pangolins, where pangolin researchers may have less experience of the species and methods used to monitor them (e.g. armadillos and gopher tortoises). Furthermore, the selected species largely do not produce far-reaching vocalisations from which one could accurately identify the species (like pangolins), they vary in the strength of their eye-shine when conducting nocturnal spotlight surveys (as pangolins have low eye-shine [reported for the Chinese and Sunda pangolin; Newton et al., 2008]) and in the difficulty by which scats and/or latrines are to find.

A list of ecologically similar species was identified through consultation with members of the IUCN SSC Pangolin Specialist Group. A full list of the species originally identified and reasons for exclusion can be found in Appendix 1. The final list considered in the review is shown in Table 2. Whilst the list of possible species is not exhaustive, acknowledging that there are likely studies on other species that would provide relevant information, given resources and the scope of this review, we believe the chosen subset provide valuable insights of relevance for pangolin monitoring.

2.2. Search strategy

We searched the Thomson Reuters Web of Science (All databases) using the following search string and Boolean terms: ("Lasiorhinus latifrons" OR "Priodontes maximus" OR "Orycteropus afer" OR "Perodicticus" OR "Tamandua" OR "Myrmecophaga tridactyla" OR "Bradypus" OR "Choloepus" OR "Dendrolagus" OR "Potos flavus" OR "Spilocuscus" OR "Ailurops" OR "Phalanger" OR "Tachyglossus aculeatus" OR "Proteles cristata" OR "Daubentonia madagascariensis" OR "Dendrohyrax arboreus" OR "Dasypus" OR "Gopherus polyphemus" OR "Cabassous" OR "Chaetophractus" OR "Euphractus sexcinctus" OR "Tolypeutes" OR "Zaedyus pichiy") AND (monitor × OR detect × OR survey × OR census*) AND (population × OR abundance × OR presence*) NOT (disease × OR parasite*). We optimised search terms before making the main searches (see Appendix 2).

Table 2

List of species, and their characteristics, that are ecologically similar to pangolins. Activity patterns: C = Crepuscular; D = Diurnal; N = Nocturnal. Locomotor categories: A = Arboreal; F = Fossorial; S = Semi-arboreal. Species are ordered by adult body mass, and body masses for genera are given as the average.

Scientific name	English name	Activity pattern ^a	Locomotor category ^a	Myrmecophagous	Solitary	Body mass (kg) ^b
<i>Perodicticus</i> spp.	Pottos	N	A		Y	1.01
<i>Tolypeutes</i> spp.	Three-banded armadillos	C, N		Y	Y	1.35
<i>Zaedyus pichiy</i>	Pichi	C, D, N	F		Y	1.50
<i>Phalanger</i> spp.	Cuscuses	N	A		Y	2.01
<i>Chaetophractus</i> spp.	Hairy armadillos	C, D, N	F	Y	Y	2.33
<i>Potos flavus</i>	Kinkajou	N	A			2.42
<i>Daubentonia madagascariensis</i>	Aye-aye	N	A		Y	2.61
<i>Dendrohyrax arboreus</i>	Eastern tree hyrax	C, N	A		Y	2.98
<i>Tachyglossus aculeatus</i>	Short-beaked echidna	C, N	F	Y	Y	3.17
<i>Cabassous</i> spp.	Naked-tailed armadillos	C, N	F	Y	Y	3.66
<i>Dasypus</i> spp.	Long-nosed armadillos	N	F	Y	Y	3.75
<i>Bradypus</i> spp.	Three-toed sloths	C, D, N	A		Y	4.07
<i>Gopherus polyphemus</i>	Gopher tortoise	C	F		Y	4.14
<i>Tamandua</i> spp.	Tamanduas	C, D, N	S	Y	Y	4.35
<i>Spilocuscus</i> spp.	Spotted cuscuses	N	A		Y	4.62
<i>Euphractus sexcinctus</i>	Six-banded armadillos	C, D	F	Y	Y	4.85
<i>Choloepus</i> spp.	Two-toed sloths	N	A		Y	5.25
<i>Ailurops</i> spp.	Bear cuscuses	D	A			7.00
<i>Proteles cristata</i>	Aardwolf	N	F	Y	Y	8.12
<i>Dendrolagus</i> spp.	Tree kangaroos	C, D, N	A		Y	8.20
<i>Lasiorhinus latifrons</i>	Southern hairy-nosed wombat	N	F		Y	26.16
<i>Myrmecophaga tridactyla</i>	Giant anteater	C, D, N		Y	Y	29.53
<i>Priodontes maximus</i>	Giant armadillo	N	F	Y	Y	45.19
<i>Orycteropus afer</i>	Aardvark	C, N	F	Y	Y	56.18

^a Locomotor category obtained from Wilman et al. (2014) – we changed G (Ground) to F (Fossorial).

^b From Myhrvold et al. (2015).

Furthermore, we supplemented our searches using Google Scholar by searching the first 10 pages of results for combinations of scientific species names and either 'population' or 'abundance'. All searches were conducted between 15 December 2017 and 2 January 2018.

2.3. Article screening

Studies were first screened using the title and abstract to remove studies that were immediately irrelevant, and the remainder screened by full text. Studies were included if they used and described one or more method of identifying the presence or abundance (or metric thereof) of our set of target species, including studies sampling all biodiversity or a subset (e.g. all mammals) at a site that happened to identify our target taxa. Behavioural studies were included if they also sought to detect individuals of a species or monitor aspects of their ecology that can inform better monitoring practices of the target species (e.g. home range, burrow use). We also included studies across all available years and countries, and review papers that discussed methods used to monitor target taxa and may therefore provide further insight. Whilst we used only search terms in English, studies in other languages were included if they contained an English abstract that provided sufficient information on the sampling method.

Studies were excluded if they: monitored the presence or abundance of diseases and parasites on target taxa; were conducted in a zoo environment; monitored non-target species only; were records from wild meat markets (given that the origin of specimens in such markets is often unknown; however, we kept information from hunting studies); or where the method of detection itself resulted in the death of the animal. Furthermore, studies were excluded if the method used to detect target species was not adequately explained and could therefore not be repeated. If papers contained an identical study/dataset in another paper, we selected the most informative in terms of the methods used.

2.4. Study information

After screening, we recorded the methods that studies used to record the presence and/or abundance (or metric thereof) of target species. In addition, we also recorded whether studies: 1) specifically set out to detect or monitor one of our target species; 2) compared methods used for detection; and 3) made note of the effectiveness of the methods used (e.g. detection, short-term monitoring, long-term monitoring, cost, precision, accuracy, sample size needs).

3. Results

3.1. Description of literature

In total, 379 articles were identified through Web of Science searches. After screening (see Fig. 1), 246 articles were included in the systematic review (Appendix 3), of which 159 were from Web of Science and 87 were from Google Scholar. Of the studies included, 224 were in English, 13 in Spanish, and 9 in Portuguese. The number of studies that detected each target taxa varied (Table 3), for example, only one of the identified studies detected pichi (*Zaedyus pichiy*), whereas 97 studies detected long-nosed armadillos (*Dasypus* spp.).

The final set of studies included in this review were published between 1969 and 2017, and were conducted in 35 countries: Angola, Argentina, Australia, Bolivia, Botswana, Brazil, Cameroon, Colombia, Costa Rica, Ecuador, Ethiopia, Equatorial Guinea, French Guinea, Gabon, Ghana, Guatemala, Honduras, Indonesia, Kenya, Madagascar, Mexico, Namibia, Nicaragua, Nigeria, Panama, Papua New Guinea, Paraguay, Peru, South Africa, Sudan, Suriname, Tanzania, Uruguay, United States of America, and Zimbabwe.

3.2. Description of methods

In total, across all studies and taxa, 28 different methods were used for detection and monitoring, of which 24 were used specifically to detect or monitor the target taxa (see Appendix 4 for all methods). Transect-based methods detected 22 of the 24 target taxonomic groups (141 studies) and were specifically chosen to monitor 16 target taxa. Camera-traps detected 13 of the target taxonomic groups, representing the method that detected the second highest number of target taxa (143 studies), but were only specifically chosen to monitor seven species or species groups.

Studies in which surveyors walked along trails to detect species, but did not follow a transect-based method, we described as 'trail surveys'. For discussion, we also grouped methods into 'plot-based methods' (e.g. quadrats, fixed-area plots), and 'tree sign surveys' (surveys of trees for: feeding signs, animal latrines, or cavities; including such methods as: dead tree surveys, tree illumination, grid-based spot assessments). Studies that used scent stations as a method were grouped into a 'track plot' category, and capture-recapture methods were included within a 'live trapping' category.

Playback surveys (1 study) and hair sampling (1) were used to detect target taxa but were not included because they were deemed inappropriate for the surveying of pangolins due to the lack of vocalisation and limited amount of hair on pangolins. We also omitted records where target taxa were detected purely opportunistically (19 occasions), or through random trail surveys (9).

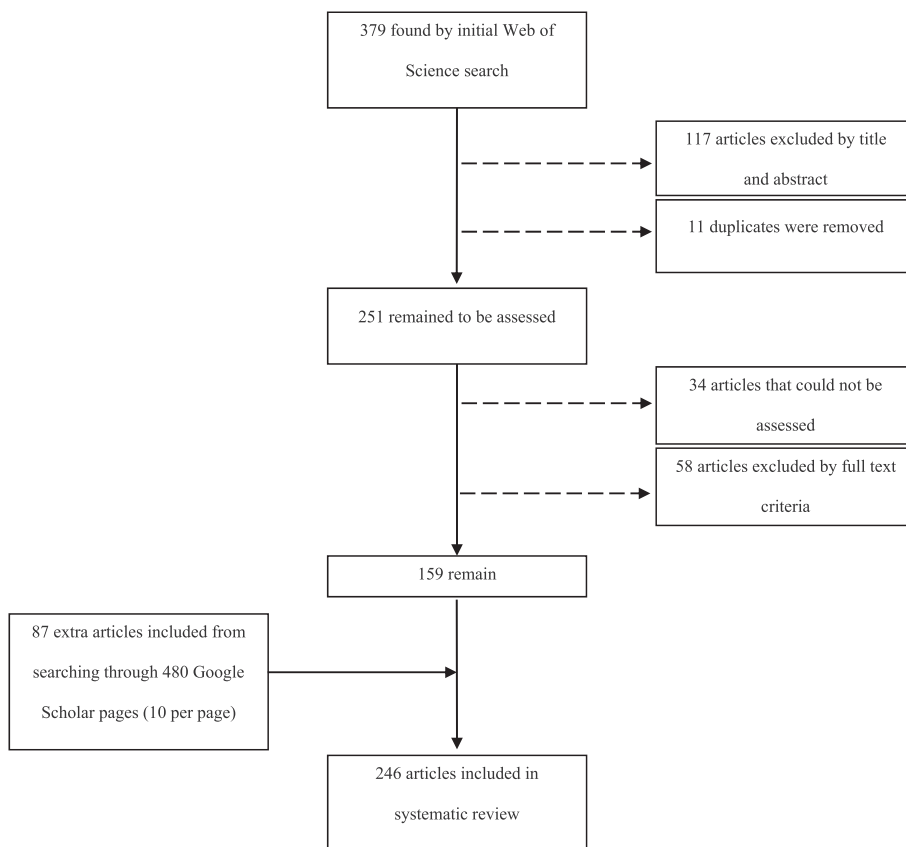


Fig. 1. Flowchart of the article screening process.

Below, we compare the methods used to monitor target taxa in terms of their relative effectiveness based on the information acquired from the studies, and then discuss their potential application to monitoring pangolins.

4. Discussion

A variety of methods were used to detect the presence of target species, including both direct and indirect methods. Here, we discuss the studies that provided information on the efficacy of the methods used to monitor the target taxa, and that may be useful for monitoring pangolins. However, it is important to note that not all studies provided details conducive to this review, so we have relied on the information that was available and interpreted available information on effectiveness accordingly (e.g. considered detection rate when interpreting camera traps as a method). Whilst we primarily discuss methods under each of the subheadings below, we have included information from studies that compared two or more methods at the same time where appropriate.

4.1. Direct sighting surveys

Direct sighting surveys include methods whereby the surveyor will directly observe and count each animal; they can be conducted in a wide variety of ways, for example transects, plots and trail surveys; and can be conducted during the day or night. Thorough reviews of these differences are already available elsewhere (Buckland et al., 1993; Borchers et al., 2004; Thompson, 2004).

4.1.1. Transects

The number of individuals of a given species can be estimated by walking along pre-determined transects, and quantifying individuals seen and their tracks and other field signs (e.g. burrows). Transects are useful for calculating abundance estimates, from which density can be estimated for a given area using distance sampling (Buckland et al., 1993). The pros and cons of using transects have been discussed at length (Buckland et al., 1993), so here we discuss the challenges and use of them for our target taxa.

Table 3

Number of studies identified from the systematic review that detected target taxa.

Scientific name	English name	Number of studies that detected target taxa
<i>Perodicticus</i> spp.	Pottos	9
<i>Tolypeutes</i> spp.	Three-banded armadillos	5
<i>Zaedyus pichiy</i>	Pichi	1
<i>Phalanger</i> spp.	Cuscuses	5
<i>Chaetophractus</i> spp.	Hairy armadillos	10
<i>Potos flavus</i>	Kinkajou	29
<i>Daubentonia madagascariensis</i>	Aye-aye	7
<i>Dendrohyrax arboreus</i>	Eastern tree hyrax	7
<i>Tachyglossus aculeatus</i>	Short-beaked echidna	7
<i>Cabassous</i> spp.	Naked-tailed armadillos	25
<i>Dasypus</i> spp.	Long-nosed armadillos	97
<i>Bradypus</i> spp.	Three-toed sloths	23
<i>Gopherus polyphemus</i>	Gopher tortoise	33
<i>Tamandua</i> spp.	Tamanduas	72
<i>Spilocus</i> spp.	Spotted cuscuses	3
<i>Euphractus sexcinctus</i>	Six-banded armadillos	31
<i>Choloepus</i> spp.	Two-toed sloths	16
<i>Ailurops</i> spp.	Bear cuscuses	3
<i>Proteles cristata</i>	Aardwolf	5
<i>Dendrolagus</i> spp.	Tree kangaroos	5
<i>Lasiorhinus latifrons</i>	Southern hairy-nosed wombat	2
<i>Myrmecophaga tridactyla</i>	Giant anteater	59
<i>Priodontes maximus</i>	Giant armadillo	44
<i>Oryzomys afer</i>	Aardvark	10

The effort required to detect every species present in a community and gain a representative sample of an entire species community assemblage can be high when elusive species are present, the required sampling area can be vast, and thus rapid surveys are unlikely to detect every species (Romero et al., 2016), especially when encounter rates are low. For the giant anteater, for which encounter rates are generally low, Desbiez and Medri (2010) suggest that line transects are an inefficient method to estimate population densities. This sentiment is mirrored by Timock and Vaughan (2002) and Mathai et al. (2013), who considered that transects have limited application for estimating populations of inconspicuous, rare, or evasive animals, e.g. sloths, because encounter rates are low. Furthermore, as visibility differs between sites (e.g. due to vegetation), the ability to detect species also differs between sites (and may be influenced by researcher experience), which is particularly a problem for species whose detectability may be low already (Denis et al., 2017). Furthermore, the validity of distance-sampling methods for burrowing species should be considered when selecting methods. Distance-sampling methods require that every animal at zero distance of the transect midline will a) be detected with certainty, and b) be detected at its original position (Buckland et al., 1993); however, given that pangolins are often in burrows, this requirement is unlikely to be met.

Nocturnal transects can be conducted to target nocturnal species (e.g. Lumholtz's tree-kangaroo; Kanowski et al., 2008), usually looking for eye-shine when searching with a torch ('spotlighting'). However, these methods are not universally applicable; Pereira Munari et al. (2011) found that night transects performed poorly for nearly all species, including for long-nosed armadillo. The authors suggest that the detection and successful identification of animals is hindered at night by the limited field of vision and longer time required to identify animals at night. Using a combination of camera-traps, track transects, and vehicle-based nocturnal transects, Kasper et al. (2007) confirmed presence of target taxa (naked-tailed armadillos, six-banded armadillos, and tamanduas) only from camera-trapping. Furthermore, animals differ in the strength of their eye-shine (Ollivier et al., 2004), which means that they may not be detected in nocturnal spotlight surveys. Nocturnal transects may therefore be of limited use for pangolins, for which limited eye-shine has been reported (Newton et al., 2008).

Several other transect-based methods have been used to detect the ground-dwelling, larger-bodied target species. For example, using aerial surveys Mourão et al. (1994) detected giant anteaters and de Miranda et al. (2006) estimated giant anteater density. Whilst aerial surveys were found to be suitable for flat, open terrain, they have high operational costs and are of limited use for closed habitats. Aerial surveys are unlikely to be of use for surveying pangolins, given that they occur at low densities and are primarily nocturnal. It may be possible to locate potential pangolin burrows with low-flying aeroplanes or drones in open arid areas where Temminck's ground pangolin occurs. However, the cost and practicalities of this approach are likely to be prohibitive. Terrain is known to influence the reliability of transects. For example, Timock and Vaughan (2002) suggest that sampling in steep terrain can change the speed at which the surveyor walks the transect line, which could affect the amount of time spent searching for target species, and the comparability with other transects. However, researchers have navigated terrain using vehicles (e.g. Silveira et al., 1999), and bicycles have allowed local communities to monitor savannah wildlife following line transect principles in a relatively cheap participatory manner (e.g. Gaidet et al., 2003). The use of bicycles may be a useful, cheap, and time-efficient way of locating potential pangolin burrows over larger, more open areas, particularly for Temminck's ground pangolin, which occurs in such habitats.

Rather than using transects or distance-sampling based methods to find individuals, for burrowing species it may be more appropriate to use them to find dens or burrows e.g. as is done for gopher tortoises (Castellon et al., 2015). Discussion on the identification of burrows and estimation of abundance from burrow counts can be found in Section 4.3.

4.2. Camera-trapping

4.2.1. Ground-level camera-traps

Camera-traps have gained traction in the monitoring of elusive species (e.g. carnivores; Karanth and Nichols, 1998; Belant et al., 2013) and are considered one of the least intrusive methods of monitoring wildlife (O'Connell et al., 2011), compared to other methods such as line transects which often involve cutting paths on which to conduct transects. Further, reviewed literature reported that they were particularly suitable for animals with a body mass >1 kg (Espartosa et al., 2011; Motta Lessa et al., 2017). Several publications are now available that describe the use, pros and cons, and considerations for linking camera trap surveys to ecological processes (O'Connell et al., 2011; Burton et al., 2015; Wearn and Glover-Kapfer, 2017), therefore here we concentrate on the application of camera traps to pangolins.

Camera-traps were the second-most-used method across studies but for the main part were not specifically chosen to monitor the target species. The target taxa that were most frequently detected by camera-traps across studies were long-nosed armadillos and tamanduas in 37 and 30 studies respectively. Studies varied in their detection rate, although we note that detection rate can be influenced by the position of the cameras, which differed between studies. For example, tamandua were detected between 0.06 (1611 trap nights in a tropical rainforest, with cameras deployed 60 cm above ground-level; Arroyo-Arce et al., 2016) and 0.2 (estimated 1169 trap nights in a grassland with cameras 1.5 km apart; Silveira et al., 2003) detections per 100 camera-trap nights. Long-nosed armadillos were detected between 0.16 (1279 trap nights in a tropical dry forest with cameras placed at a height of 30–40 cm in pairs at least 200 m apart; Kosydar et al., 2014) and 0.99 (Arroyo-Arce et al., 2016) detections per 100 camera-trap nights. Even with a much larger survey effort (29,618 camera-trap nights), one study reported similar detection rates for tamandua (31 detections; 0.08 detections per 100 camera-trap nights) and long-nosed armadillo (75 detections; 0.25 detections per 100 trap-nights; Zimbres et al., 2013, with cameras deployed at least 2 km apart). Long-nosed armadillos are fossorial (Abba and Superina, 2016), whilst tamandua are typically semi-arboreal, occasionally descending to the ground to forage (Desbiez and Medri, 2010; Brown et al., 2014). Given that the fossorial and semi-arboreal species listed above were successfully detected, and the body masses of these genera are ~4 kg, camera-traps may be particularly effective for fossorial Chinese pangolin, and semi-arboreal Philippine pangolin and Sunda pangolin. Unlike many elusive carnivores, pangolins have been observed moving through dense vegetation, so random camera placement may yield better results for pangolins, as suggested by Gray et al. (2017). However, it is important to note that the population densities of both target genera may be higher than that of the three aforementioned pangolin species, and that non-targeted camera-trapping has been ineffective at producing records for these three species (e.g. Newton et al., 2008; Willcox et al., 2019).

Espartosa et al. (2011) compared the use of camera-traps and track plots (in sand) to monitor wildlife (including our target taxa) and found that both methods performed similarly in terms of species richness and variation across space. In addition, they found that while the initial financial investment to purchase and maintain camera-traps was high, track plots required greater investment in terms of personnel time to set-up and survey plots. Furthermore, surveying track plots requires dry weather prior to and during surveys, and suitable substrate from which to count tracks, although it should be noted that camera trap functionality was reduced in high humidity.

A comparative methods paper reported that camera-traps performed better than diurnal and nocturnal transects (Pereira Munari et al., 2011), because some species were not recorded at all on nocturnal transects. One study evaluated camera trap use, including for target taxa (giant anteater, tamandua, long-nosed armadillo), and found that while camera spacing had little effect on the number of species recorded, survey effort significantly influenced it (Tobler et al., 2008). Capture probabilities were found to decrease with decreasing size of species (Tobler et al., 2008). To record rare and elusive species (here giant anteater, giant armadillo, and tamandua) that may be present at a site, Tobler et al. (2008) suggested that a sample size of 1000–2000 camera-trap nights is required. However, the same study reported that even with 3840 camera nights, some of the rarest species were recorded from three or fewer photos (2 photos of giant anteater, 3 of nine-banded long-nosed armadillo), suggesting that significant effort may be required where densities are low. Whilst pangolins are generally thought to occur at low densities, pangolin densities are likely even lower in areas where hunting pressure has been or is high. This is particularly likely for the Asian pangolins, and for black-bellied and giant pangolins in West and Central Africa. Therefore, given the effort needed to record the giant anteater, serious consideration is needed to decide whether the cost and effort of a passive camera-trap survey would be worth it for monitoring pangolin populations. It may be worth conducting a survey for burrows or signs (although see discussion on these methods), or active targeting at signs using camera-traps, to gauge a preliminary understanding of possible pangolin densities.

For the largest of the target taxa, giant armadillos (*P. maximus*, ~45 kg), the most common monitoring methods chosen were camera-traps (20 studies). Giant armadillos inhabit open grassland areas like the Cerrado in Brazil, and tropical rain forests. A comparison of camera-trapping (24,840 h) and track surveys (30,600 h survey effort) yielded 0.3 and 3.5 records of giant armadillos per 100 days respectively (estimated from table in Silveira et al., 2003) on a two-month survey conducted in

the Brazilian grasslands. The authors note that both methods can overestimate abundance but suggest that camera-trapping is less susceptible to overestimation because a chain of photos in quick succession are attributed to the same individual, whereas multiple tracks cannot be attributed to individuals (Silveira et al., 2003). In forested and fragmented areas, photo capture rates of between 0.07 and 0.16 photos per 100 trap-nights were recorded in Bolivia with a sample size of between ~1300 and 1500 trap-nights per site (Kosydar et al., 2014). In Brazilian secondary tropical rain forests, sampling durations of ~500 and 1700 trap-nights per site/season resulted in 0.275 and 0.358 detections of giant armadillos per 100 trap-nights (Negrões et al., 2011). In undisturbed lowland rain forests in Ecuador, 5547 trap-nights yielded a mean photo capture rate of 0.56 (Blake et al., 2017). The size, habitat preferences, and rarity of giant armadillo suggest that the methods used to monitor this species may be useful for monitoring the giant pangolin (and potentially Indian and Temminck's ground pangolin), although greater knowledge of giant pangolin ecology is needed and testing of monitoring methods is required. However, Wahyudi and Stuebing (2013) note that non-detections of pangolins are possible when using infrared camera-traps if the temperature difference between the scaly body of a pangolin and the surrounding environment is not sufficiently different. Furthermore, fossorial species may also be covered in mud, which could potentially affect this temperature difference. We therefore suggest field testing of this, and if true, follow-up testing of camera-traps that are not triggered by a temperature difference.

4.2.2. Arboreal camera-traps

Arboreal camera-traps have been used to detect and monitor kinkajou in cloud forests in Guatemala (19 detections over 902 sampling days; Rivas-Romero and Soto-Shoender, 2015). Over 3608 trap-nights in primary rainforest in Peru, Gregory et al. (2014) detected kinkajou at a rate of 8.76 events per 100 trap nights, tamandua at 0.22 and two-toed sloth at 0.08. Based on these studies, we suggest that arboreal camera traps should be trialled for white-bellied, black-bellied and Sunda pangolins, given similarities in their ecologies.

Gregory et al. (2014) suggested that placing camera-traps in trees is a robust method of monitoring arboreal wildlife but found that leaf movements resulted in many false triggers. The authors demonstrated that removing leaves within 1.5 m of cameras reduced the number of times the camera was triggered by non-target stimuli. Whilst the same study found no negative response by wildlife to the cameras, Schipper (2007) found some evidence of avoidance behaviour in kinkajou. Gregory et al. (2014) found that 30% of the arboreal camera-traps malfunctioned, which was similar or less than the 27–54% that malfunctioned during ground surveys. To reduce malfunction rates, two methods were suggested: 1) use stainless steel wool and/or petroleum jelly around the housing and base to reduce insect invasion, and 2) conduct camera maintenance on dry days, and use silica gel inside the camera to avoid condensation. Studies should consider and investigate whether the addition of protective substances to camera traps (e.g. petroleum jelly), affects the behaviour of target species.

4.3. Den/burrow counts

As with direct sighting surveys, identifying and counting burrows can be conducted in a variety of ways such as along transects, or in quadrat/plot-based surveys (see Section 4.1.1). In this section, we discuss the identification of burrows, burrow characteristics, and ways in which studies identified that dens or burrows were occupied by target taxa.

The detection of fossorial species is challenging but this review found a variety of methods that have been used to detect the fossorial species themselves, or to estimate the number of individuals in a population based on the rate of occupied burrows. Of the fossorial taxa included in our review, we found the largest number of studies detected long-nosed armadillos (117 studies), giant armadillo (53), gopher tortoises (40), six-banded armadillo (36), and naked-tailed armadillos (26).

For the smaller-bodied fossorial species, such as gopher tortoise, hairy armadillo, and long-nosed armadillo, transects have often targeted burrows rather than the animals themselves (e.g. Castellon et al., 2015). Transects are thought to better reflect spatial variability than plot-based methods and allow for imperfect detection through distance sampling (Buckland et al., 1993; Castellon et al., 2012). For studies that detected burrows, a set of criteria to categorise the activity status of the burrow is subsequently applied. Characteristics used to identify the activity status of a burrow include 1) recent tracks, and 2) a clear burrow apron (the mound of soil immediately outside a burrow entrance) that is free from vegetation. A 'fresh' burrow may be categorised differently for each species and habitat type, which is important to consider when comparing burrow densities between studies. Studies were also found that identified species directly from the shape and characteristics of the burrow itself (e.g. long-nosed and hairy armadillos; Abba et al., 2007). However, Arteaga & Venticinque (2012) considered that this method is inaccurate due to complications with identifying whether burrows are inhabited by different species, or different size classes of the target species. Methods used to estimate population sizes based on the activity status of burrows rely on robust survey methods and some studies suggest a correction factor can be applied between burrows and the number of individuals. For gopher tortoises, one study found that the number of 'active burrows' best represented the number of actual tortoises ($R = 0.9$, McCoy and Mushinsky, 1992), rather than incorporating inactive burrows into estimates. However, Stober and Smith (2010) found that the use of a correction factor overestimated their population size by 39–64%. It should be noted that using gopher tortoises as a comparator species for pangolins is not without complications, given the relatively high abundance of the species within suitable habitats (Berish et al., 2012). However, the principles outlined here could first be trialled with fossorial pangolin species, particularly in open sandy terrain, and where populations are not severely depleted.

Other than external burrow characteristics, four different methods have been used determine whether a burrow was occupied for species included in this review. For gopher tortoise, burrow excavations have been conducted (Witz et al., 1991),

as well as sticks (Burke, 1989) and camera-traps (Ferregueti et al., 2016) placed in front of entrances, though the most common method to determine if a burrow is occupied is the use of a flexible burrow camera (e.g. Castellon et al., 2012). The 'stick method' is thought to be inaccurate (due to target species using multiple burrows) and can overestimate population size (Burke, 1989). Burrow cameras are thought to be the most accurate, however it can be difficult to assess the presence of an animal in inclement weather, or when roots are present inside burrows obstructing the view (Castellon et al., 2012, 2015). In a comparative study, Smith et al. (2005) found that using external burrow characteristics to determine presence was highly subjective and related to the experience of the surveyor. Any calculations of population size based on burrow presence therefore need to be considered carefully for pangolins because of multiple burrow use by fossorial species over short periods of time. Pangolins may also use a resting structure (including a burrow) for 2–3 nights and then move on to another (e.g. Chinese pangolins; Lin, 2011); therefore, estimating population size based on actively used burrows requires further testing, consideration of burrow types (i.e. resting and feeding burrows) to reduce bias, a better understanding of pangolin ecology, and careful interpretation.

Remote methods such as satellites have also been suggested as a method to count burrows in open areas where burrows contrast with the surrounding vegetation, e.g. as used for the Southern hairy-nosed wombats (Loffler and Margules, 1980). Whilst no other remote methods were found in this study, similar results may be achieved using drone technology over flat open areas to search for burrows. However, additional surveyors on the ground would be needed to confirm whether a burrow was active, and whether it was used by a pangolin or another species.

For arboreal species that nest in cavities, searches of signs in tree cavities have been used for cuscus, but these censuses were found to yield inaccurate results after comparison with felled trees (Warakai et al., 2013). The same study placed artificial nest boxes in trees to determine the presence of cuscus in the area, which were found to be successfully used by cuscus. This method could be useful for determining the presence of arboreal pangolin species such as white-bellied and black-bellied pangolin, but this would require field testing and evaluation, including an assessment of whether use of these structures could have adverse consequences e.g., provide an easy means for poachers to collect pangolins.

4.4. Trapping

Live trapping methods were used in a variety of different studies to investigate aspects of the ecology and demography of the target taxa. Tomahawk traps were commonly used to capture medium and large-bodied ground-dwelling and arboreal mammals including kinkajou and echidnas (e.g. Julien-Laferriere, 1993; Lilit et al., 2010). Kays (1999) used 50 large baited Tomahawk traps in trees for 1292 trap-nights over a year and successfully caught 25 individual kinkajous on 192 occasions. Studies baited traps with bananas for kinkajou and achieved success (Kays, 1999), though it is unclear how successful these methods would be for pangolins given their strict dietary requirements. Although not a food-based bait, for nine-banded armadillos Martin et al. (2014) found that using a conspecific attractant acquired by placing a live individual in a trap overnight was 8.3 times more effective than a reference trap alone. Putting traps directly outside 'active' burrows may work, as was successful for Tuberville et al. (2014) in their study on gopher tortoises. Pangolins may injure themselves in metal box traps, but mesh traps could be successful, as with the Indian pangolin in Pakistan (Mahmood et al., 2016).

Capture-recapture studies were successfully conducted on hairy armadillos (Abba et al., 2011a), long-nosed armadillos (Abba et al., 2011b), naked-tailed armadillos (Bonato et al., 2008), and gopher tortoises (Tuberville et al., 2014) to estimate abundance. Following live trapping, individuals were often fitted with VHF radio transmitters to estimate home ranges (e.g. telemetry tags on tamanduas attached to the lower back with 5-min epoxy (Brown et al., 2014), and VHF radio-transmitters attached to maned three-toed sloths using ball-chain collars (Falconi et al., 2015)), or temperature loggers to infer activity patterns (e.g. yellow and nine-banded armadillos in Maccarini et al., [2015]). Both radio-trackers and temperature-loggers enable other detection methods to be tailored to particular species. For example, knowing the typical home range and activity pattern of a species of pangolin (as is available for Chinese pangolin (Pei et al., 2015), Philippine pangolin (Schoppe and Alvarado, 2015), Sunda pangolin (Lim and Ng, 2008), and Temminck's ground pangolin (Pietersen et al., 2014b)) would enable appropriate sampling unit size to be determined e.g. suitably spaced camera matrix to be used, or transects conducted at times of peak activity. Maccarini et al. (2015) used two methods to attach transmitters 1) rubber strips and/or layered adhesive tape on the armadillo's tail, and 2) other devices attached with cables through holes drilled into the carapace (an anaesthetic was used during this procedure). Tracking could be utilised to gain a better understanding of basic ecological parameters for pangolins, which are currently lacking for many species, however designing appropriate lightweight and durable tags is still needed for several pangolin species (e.g. Sunda pangolin).

4.5. Sign surveys

Track plots were used to determine presence, metrics of relative abundance, and habitat use for a subset of our target taxa, including six-banded armadillo, long-nosed armadillo, giant armadillo, giant anteater and tamandua (Lacerda et al., 2009). Track plots involve clearing plots of foliage before a survey and checking plots for tracks (i.e. footprints) systematically. Nachman (1993) used scent stations along track transects and detected long-nosed armadillo and kinkajou. In comparison to line transects, the authors note that scent stations take longer to set up initially, but that line transects require more survey effort. Disadvantages of this method include the need to clear tracks between surveys, and its unsuitability in wet weather

conditions e.g. tropical rainforest. However, the author recommended this method as a simple and inexpensive means of monitoring wildlife (Nachman, 1993).

Signs based on the locomotor or feeding activities of animals were also used to monitor target taxa. Heise-Pavlov et al. (2011) used a grid-based survey method for assessing the presence and use of trees by tree kangaroos, Miller et al. (2017) surveyed dead trees for characteristic feeding signs of aye-aye, and Gaylard and Kerley (2001) used lights to search the interiors of trees to determine presence of tree hyrax by detecting latrines. Whilst sign-based methods can provide a metric of relative abundance, they provide no information on population size (Crawford, 1991), and metrics of relative abundance have also been heavily criticised for being inaccurate and unreliable (Sollmann et al. 2013). For detecting the presence of pangolins, these methods may be useful, even if just initially to inform more targeted monitoring. Current evidence suggests that only ground-dwelling species leave signs that enable detection, such as Temminck's ground pangolin that leaves tail and foot tracks in the sand (Pietersen et al., 2014b; Willcox et al., 2019), however even these may be misidentified (Godwill et al., 2017), so caution should be exercised and ideally species identification confirmed by camera trap.

4.6. Detection dogs

Dogs have been used in wildlife research and management in a variety of ways such as the detection of living animals, carcasses, or signs such as scats (Dahlgren et al., 2012). For our target taxa, Vynne et al. (2011) and Silveira et al. (2009) systematically surveyed areas with trained scat-detection dogs in Brazil to specifically detect giant armadillo. The former study found that occurrence probabilities could be assigned using this method, and that the effort required was less than that required to monitor felids. Both studies note that scat detection dogs are particularly suitable for the detection of rare species, and thus may be particularly suitable for pangolins, especially where populations are depleted e.g. large parts of South-east Asia. However, black-bellied pangolins have been observed defecating in small tree hollows/cavities (R. Cassidy pers. comms.), which regularly fill with water, and Sunda pangolins have been observed defecating in water bowls in captivity (D. Willcox pers. comms.). If this behaviour is common in the wild, it would reduce the detectability of pangolins per unit survey effort.

4.7. Other methods

Several other methods used in the studies reviewed are suitable for determining presence, but not always to a species level, for example, interviews with local people (e.g. informal, semi-structured, and postal surveys), opportunistic sightings, road kill surveys, and hunting surveys (see Willcox et al., (2019) on their application to pangolins).

4.8. Application for monitoring pangolins

For the primarily arboreal and diurnal black-bellied pangolin, arboreal camera-traps may be useful for determining presence. Transects and cavity nest searches may also be useful for this purpose. However, all these methods require piloting and field testing. Moreover, several ecological questions need to be addressed first. In particular, home ranges need to be estimated, and the height in the trees at which black-bellied pangolins rest or are most active are as of yet largely unknown. The ability to accurately identify rest areas (e.g. tree cavities, preferred tree species) used by white-bellied and black-bellied pangolins also needs to be determined.

For pangolins that are semi-arboreal (white-bellied, Sunda, and Philippine pangolins), camera-traps (arboreal and ground) may be useful for detecting and monitoring pangolin populations based on detection rates for ecologically similar species (see discussion on tamandua and long-nosed armadillo in the camera-trap section above). However, this will be more challenging for the Asian species (Sunda and Philippine pangolin), given low population densities in many places due to overexploitation (Willcox et al., 2019).

Whilst pangolins are thought to have poor eyesight, they are also thought to use their well-developed olfactory senses to detect predators (Israel et al., 1987). Baits were occasionally used for camera trapping and live trapping, and scent stations were used along transects; however, considering the specialised diet of pangolins, little is known about the effectiveness of baiting for pangolins. One study found no effect of any bait type tested for Philippine pangolin (Marler, 2016), although bait types used were inappropriate given the species diet. However, for nine-banded armadillos, the use of a conspecific attractant increased effectiveness by 8.3 times in comparison to a reference trap alone (Martin et al., 2014).

For fossorial pangolins (Chinese, Temminck's ground, Indian, and giant pangolins), the use of transects to find burrows, combined with methods to assess the activity status of burrows, could be successful. To monitor the activities of these largely ground-dwelling species of pangolins, camera-traps are likely to be the most successful given that 1) they can detect individuals at all times of day and night, and 2) they have been successful for monitoring the similarly-sized and sparsely-distributed armadillos in this review. However, passive monitoring methods such as camera traps may be limited in areas where populations occur at low densities, and as such more active methods or proxy methods based on burrow presence may be needed.

Further information is needed on whether pangolins leave unique signs, which could be used to identify their presence, and on the number of pangolins that use/inhabit each burrow. Additionally, Temminck's ground pangolins have been found to rarely excavate their own burrow (Pietersen et al., 2014b), so unique detectable signs in the burrows of other burrowing species could be useful. Seasonality of burrow use, home range size, and activity patterns, as shown for the Chinese pangolin

(Lin, 2011), should be considered for all species because this may affect burrow counts and detections by camera-traps and transects. Research is therefore needed to discern whether methods to monitor pangolins based on burrow activity status and conversion factors could be appropriate.

5. Conclusions

Camera-traps and transects (to count burrows rather than individuals) appear to be the most successful methods for monitoring ecologically similar species to pangolins. Furthermore, methods that assess whether dens/burrows are actively used, and methods that identify the number of occupants in a burrow were found to be particularly relevant for monitoring pangolin populations. Despite the number of relevant studies and methods that exist for informing the monitoring of pangolin populations (e.g. burrow counts, and arboreal camera-trapping), several questions on the ecology of pangolins remain to be answered to further inform the most appropriate methods.

Conflicts of interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gecco.2019.e00632>.

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