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Original article

Surveying biodiversity of soil herpetofauna: towards a standard quantitative methodology

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Abstract

Soil herpetofauna biodiversity is conservatively estimated as 2775 species, made up of 10% and 28% of Amphibia and Squamata, respectively. Neglect in their taxonomy, ecology and standard sampling methodologies suggests that proportions, as well as numbers, are likely to be far higher. Like invertebrate soil macrofauna, the majority of species live within the first few centimetres of leaf litter and soil. Results of 30 quantitative and 52 semi-quantitative surveys in nine regions of three continents show that these are infrequently encountered, whereas dedicated subterranean burrowers can be found at high densities, up to 0.844 individuals m^{-2} ($\bar{x} = 0.26$). This suggests that a two tier sampling approach may be most appropriate, with superficial excavations in a large quadrat (e.g. 25 m^2) in addition to a smaller deeper subsample. It is hoped that this contribution will stimulate further discussion towards a consensus, filling the gap for a standard method of quantitative surveying of soil herpetofauna biodiversity.

Keywords: Standardised surveys; Scolecophidian snakes; Gymnophiona; Amphisbaenians

1. Introduction

It is widely recognised that soil flora and fauna have lagged behind their terrestrial counterparts in terms of ecological studies [1]. Furthermore, the relatively few taxonomic studies on soil organisms have resulted in an under appreciation of their importance to biodiversity [2]. Soil herpetofauna, reptiles and amphibians, are no exception. For example, Biju and Bossuyt [3] recently described a new family of anurans from a single specimen of a fossorial species, a feat considered to be similar to the first discovery of a living coelacanth [4].

Historically, the discovery and description of soil herpetofauna has been like that of all other flora and fauna, relying on natural historians and the simply curious depositing specimens in museum collections [5]. Although these valuable specimens have served as a useful starting point, many species are only known from the very few individuals that were originally collected [6], and sometimes important details are missing from information associated with these specimens [7]. Even when collections have been extensively documented, resulting data can be of limited comparative use unless standard sampling methodologies have been followed. At present, for soil herpetofauna, no widely accepted standard sampling methods exist [8,9].

Do we need standard techniques to survey the biodiversity of soil herpetofauna? Biodiversity assessments require proven techniques [8], and it is becoming clear that these are not capable of finding apparently common fossorial herpetofaunal taxa [10,11]. Clearly for

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the taxa concerned special searching methods are required which should be standardised for comparative purposes. Including searches which provide estimates of soil herpetofauna presence or abundance would increase the value of biodiversity surveys in the soil ecosystem. Wolters [12] noted that alteration in species composition is probably not a random process, and it may be that soil herpetofauna (and amphibians in particular) as top predators might act as indicators of wider problems in the soil community, just as they are known to do in terrestrial and aquatic systems [13].

The purpose of this contribution is to: 1. Provide an appreciation of the biodiversity of soil herpetofauna, with a preliminary attempt at quantification of the number of species; and 2. to critically compare the results of semi-quantitative and quantitative soil herpetofauna biodiversity surveys in order to move toward a standard methodology.

2. An appreciation of the biodiversity of soil herpetofauna

At first inspection, two soil herpetofauna groups appear to be separated ecologically: those which use the soil (*sensu lato*, including leaf litter, wood, etc. [2]) as a refuge (often for aestivation, or diel/nocturnal refuge with relatively stable temperature, pH, humidity), and those which are truly subterranean for the majority of their lives, reproducing in the soil, eating soil macrofauna, and rarely reaching the surface. However, the two groups are not so easily differentiated, especially when the life history of most soil herpetofauna is unknown. Intermediary forms are known (subterranean-terrestrial or subterranean-aquatic [14, 15]) which makes the assessment even more difficult. Use of the soil may also be related to ontogeny [15], and to complicate matters further, there are certain species which appear to be flexible enough to be either completely subterranean or predominantly epigeic depending on the habitat in which they are found [16]. That notwithstanding, the inclusion of these taxa within soil fauna is demonstrated by their dependence on soil macroinvertebrate prey items [16–18].

Given these difficulties and the overwhelming lack of ecological data on the majority of species involved, it is doubtful that working definitions separating groups are useful. However, it is important to bear in mind that there is almost certainly a gradation of life styles between the extremes of animals which rarely enter the soil (*sensu stricto*), and those that rarely leave it. Rather like their soil macrofauna prey (or perhaps as a result) most soil herpetofauna appear to be concentrated in the upper layers of the soil and its associated litter. It is for these reasons that a *sensu lato* definition of soil (see above) is seen as the most appropriate to adopt. It is recognised that as more, particularly ecological, information becomes available on these groups, better working definitions may appear.

All orders of Amphibia have soil dwelling representatives and one, the Gymnophiona or caecilians, are almost entirely made up of limbless, tropical, subterranean species (Table 1). Many salamanders (Caudata) are soil dwelling for part of their lives, and some frogs regularly burrow into the soil, leaving this refuge for only relatively short periods [19]. The global distribution of amphibians has recently been discussed, with the majority of species being found within the forested tropics [20].

Among the Reptilia only the Order Squamata is considered here. No members of the Order Crocodilia are recognised as being primarily subterranean, despite constructing burrows. Tuataras (Order Rhynchocephalia) inhabit burrows and occasionally eat soil macrofauna but the majority of prey are not of subterranean or leaf litter origin. Some tortoises and turtles (Order Testudines), especially within the family Testudinidae, construct and inhabit burrows, although as none eat soil macrofauna (instead foraging herbivorously on the surface) they are also excluded from this discussion.

Table 1 highlights several groups which are exclusively subterranean, in particular the amphisbaenians and scolocophidian snakes. Another reason why biodiversity of soil herpetofauna is often underappreciated is the superficial resemblance of some forms due to their subterranean lifestyle (Fig. 1). Many species have undergone body elongation, lost limbs, have similar feeding mechanics, skin and scale structure, and changes in sensory systems (e.g. reduction of eyes and covering of orbit, Fig. 1) These superficial resemblances are partly responsible for inappropriate taxonomic determinations as even closely related species may appear similar morphologically.

Difficulties in taxonomy, lack of sufficient sampling, and an inadequate understanding of ecology are probably the major impediments to determining an accurate estimate for the total biodiversity of soil herpetofauna. More importantly, it is considered that these are more extreme in soil dwelling species than their terrestrial or aquatic counterparts. Hence both proportions and numbers of species given in Table 1 are thought to be conservative estimates.

Table 1
Numbers of soil dwelling species of squamate reptiles and amphibians. Taxonomy and species numbers were taken from AmphibiaWeb (http://elib.cs.berkeley.edu/aw/ – accessed 10-08-04) and Animal Diversity Web (http://animaldiversity.ummz.umich.edu – accessed 10-08-04). See text for criteria of inclusion in soil vertebrates

Taxon		Common name	Soil dwelling species	Total species	Percent soil dwelling
REPTILIA		Reptiles			
Order Squamata			*2209*	7879	28.0
Suborder Sauria		Lizards			
	Gekkota	Geckos, blind lizards and legless lizards	*50*	1101	4.5
	Diploglossa	Glass lizards, American legless lizards, knob-scaled lizards, etc	*103*	117	88.0
	Iguania	Iguanas, chameleons, anoles, etc	*0*	1633	0.0
	Platynota	Monitor lizards	*0*	57	0.0
	Scincomorpha	Skinks, whiptails, night lizards, etc	*1244*	1919	64.8
Suborder Amphisbaenia		Worm lizards	*158*	158	100.0
Suborder Serpentes		Snakes			
	Henophidia	Boas, pythons, etc	*64*	159	40.3
	Typhlopoidea	Blind snakes	*332*	332	100.0
	Xenophidia	Colubrids, vipers, etc	*258*	2403	10.7
AMPHIBIA		Amphibians	*566*	5653	10.0
Order Anura		Frogs and toads	*174*	4963	3.5
Order Caudata		Salamanders and newts	*229*	522	43.9
Order Gymnophiona		Caecilians	*163*	168	97.0
Total herpetofauna		Amphibians and reptiles	*2775*	*13532*	*20.5*

3. Sampling of soil herpetofauna

The fundamental approach of sampling considered here is that the soil must be dug. Whilst this seems obvious, digging is not considered a standard technique for herpetological surveys [8]. Soil herpetofauna are rarely encountered at the surface, except during exceptional events such as flooding [21]. Occasional encounters, especially in pit fall traps, can skew results toward inappropriate sampling methodologies or erroneous conclusions concerning density [22,23]. Below, two methodologies are presented which have been described and used elsewhere to assess and compare densities of soil herpetofauna [9,11,24].

3.1. Semi-quantitative surveys

Several authors have remarked upon particular microhabitats which appear suitable for soil herpetofauna. These include within and under fallen and decaying logs, deep accumulations of leaf litter (in forest) or composting material and refuse (close to human inhabitations), and in close proximity to any animal captured. Often the microhabitats appear to be correlated with low soil compaction, high moisture levels and dense accumulations of macroinvertebrate prey items, although this is not always the case. However, the emphasis of semi-quantitative surveys presented here has been to target likely microhabitats, and dig into soil to an approximate depth of 0.3 m.

Semi-quantitative surveys can have, as a goal, either an area to be considered or a specific number of target taxa for study. In either case, the overall area of the survey must be approximated, as well as a quantification of the amount of effort used. A simple index calculated from this data directly relates the number of animals caught to the area searched (although not necessarily excavated) and person hours taken (i.e. individuals person hour^{-1} per area). The square root of the area searched is used to alleviate problems associated with comparing very large and very small areas [24]. The intuitive logic of this data transformation is that searching can be considered as a linear process with respect to the path taken by the searcher. The resulting index produced gives an estimation of the number of animals which could be expected to be found per hour, per kilometre searched.

Semi-quantitative surveys were always made prior to quantitative surveys, and making a quantitative survey was conditional on the success of finding the target taxon in the semi-quantitative survey [24].

3.2. Quantitative surveys

The quantitative survey method presented by Measey et al. [9] was specifically designed to use the minimum of specialist or expensive equipment, instead rely-

Fig. 1. Examples of the biodiversity of soil herpetofauna. Many diverse herpetofaunal taxa live in the soil, and while some resemble well known groups (e.g. (a) the salamander *Bolitoglossa dofleini* and (b) the rain frog *Probreviceps maculatus*), other more dedicated subterranean forms can be easily confused (e.g. (d) the blind-snake *Typhlops uluguruensis* (lighter) with the caecilian *Boulengerula uluguruensis* (darker)). Sensory systems, such as eyes, are greatly reduced (e.g. (f) the amphisbaenian *Zygaspis vandami* and the caecilian (c) *Schistometopum thomense*), while the caecilians have a specialised tentacle (seen as a small white protuberance below and forward of the eye in c). Despite their cryptic lifestyles, many species have bright colouration (like the red colubrid snake (e) *Ninia sebae* and yellow caecilian (c) *S. thomense*), although many are mostly unpigmented (d and f).

ing on inexpensive materials that are widely available in almost every country. In addition, the method specified the "ease and reasonable duration of the field work", such that surveys could be carried out by two workers within half a day.

A 10 by 10 m survey grid is produced by a 20 m length of coloured nylon rope with a loop halfway along, and contrasting markers tied at 1 m intervals. Five 1 m^2 quadrats are selected using previously determined random co-ordinates inside the grid. Three grids are laid, either side by side or at intervals of 10 m to avoid problems with micro-site selection and bias, a total of 15 m^2 is dug per survey. Digging is done with local hoes, usually a forged metal blade set at right angles to a wooden handle, to a depth of approximately 0.3 m. For other equipment used and detailed methods see Measey et al. [9].

3.3. Sites

Nine sites in six countries on three continents were visited over a period of 2 years (Table 2). They were chosen as the above mentioned methods had been used to quantify the soil herpetofauna. At each site, the study was concerned with a target taxon which was wholly subterranean (see above). Records of non-target soil herpetofauna were kept, and these are used to give an overall assessment of the merits of each sampling strategy. Each quantitative survey was carried out in approximately 2 hours.

3.4. Results

The mean overall density of soil vertebrates at all sites considered from quantitative surveys is 0.261 individuals m^{-2} (range from 0.00 to 0.844; Table 2). For semi-quantitative surveys the mean density is 230.7 individuals $hour^{-1}$ km^{-1} (range between 0.0 and 354.6; Table 2). It is notable that the variance of quantitative surveys is low, as is the total number of individuals collected, while the variance of semi-quantitative surveys is considerably higher (Table 2). Most non-target taxa were found near to the soil surface, and occur at much lower densities (Table 2).

Although semi-quantitative surveys find consistently higher numbers of taxa (Table 2) ($\bar{x} = 2.13$), compared to quantitative surveys ($\bar{x} = 1.5$), this difference was not found to be significant (two tailed paired *t*-test df = 7; *t*-stat = 1.11; $P = 0.31$). In addition, with the relatively short duration of the quantitative surveys, they appear to give a better return for effort invested.

Two noteworthy results are that despite wide searches at some sites, no target taxa were found in semi-quantitative surveys, although they were found in quantitative surveys (e.g. Ulugurus). In this same case, simultaneous surveys (semi-quantitative and quantitative) in the same area recovered more target taxa in quantitative than in the same period in semi-quantitative surveys. There are also inverse examples of both situations at other sites.

4. Discussion

Quadrat sampling is perhaps the oldest quantitative biological sampling method, and with the addition of random placement and of statistics of spatial relations [25], is still one that prevails as a standard in field biology. Krebs [26] gives three ways of defining an optimal quadrat size: statistically, ecologically and logistically. It is certain that an emphasis on any one will compromise the others. Measey et al. [9] stipulated logistic desiderata for the method used here. However, increasing quadrat size compensates for a correspondingly sparser sampling grid [27]. Jaeger and Inger [28] advocated the use of 5 by 5 m quadrats for sampling terrestrial frogs and salamanders, and this increased quadrat size would be desirable for more rigorous statistical testing. This method, with additional digging to 0.4 m, was adopted by Kupfer et al. [15] for Asian *Ichthyophis*. Indeed, the data presented here suggest that the larger the area searched (i.e. semi-quantitative surveys), the greater the biodiversity of soil herpetofauna discovered, although this result was not significant.

It is certain that the methods presented here have clear limitations for statistical use, both because of the small numbers of individuals involved, small quadrat size [27], and the limited areas covered. Although increasing quadrat size would counteract both disadvantages, this is not practical in forested habitats, where many soil herpetofauna live. In addition, little consideration has been given to the depth of digging. Most soil macrofauna are found in the top 15 cm of soil [29]. Measey [24] chose 30 cm, while Kupfer et al. [15] dug to 40 cm. Practically, deep holes with small surface areas are more difficult to achieve. Some soil herpetofauna are thought to undergo vertical migration in the soil [15,30], suggesting that during unfavourable seasons, deeper excavations may be necessary to secure at least the presence of certain taxa. However, as mentioned above, by far the majority of soil herpetofauna live within the leaf litter and first few centimetres of soil.

The biodiversity of soil herpetofauna merits a standardised survey technique which must include digging of soil. The available evidence suggests that this might be achieved on a two tier system with large areas, such as a 5 by 5 m quadrat, intensively searched to a superficial depth (e.g. 5 cm), but without disturbing trees, boulders etc. Secondly, within this, a smaller area, such as a 1 by 1 m quadrat, could be excavated to a more substantial depth (e.g. 40 cm) to determine the

Table 2
A comparison of soil herpetofauna biodiversity using semi-quantitative and quantitative surveys. Although each survey was concerned with a target taxon, the same methods were used and data on all subterranean herpetofauna found was kept. Means ($\bar{x}$) of target taxon (TT), other soil herpetofauna taxa (oT) with total number of soil herpetofauna species found (N), are presented with standard error (S.E.), and the number of surveys carried out (*N*)

Country	Area	Date	Target taxon	Quantitative frequency (m^{-2})						Semi-quantitative frequency (h^{-1} km^{-1})					
				N	**Total**	S.E.	TT	oT	*N*	*N*	**Total**	S.E.	TT	oT	*N*
Tanzania	**Ulugurus**	**November 2003**	***Boulengerula uluguruensis***	4	**0.15**	0.11	0.118	0.033	2	6	**230.1**	97.00	158.5	71.6	4
	Usambaras	**2002**	***Boulengerula boulengeri***	8	**0.50**	0.15	0.468	0.033	2	6	**354.6**	216.49	331.6	23.1	4
	Bagamoyo	**April 2003**	***Schistometopum gregori***	1	**0.00**		0.000	0.000	0	2	**200.0**	133.33	166.7	33.3	2
Kenya	**Taitas**	**2002**	***Boulengerula taitanus***	8	**0.14**	0.04	0.142	0.000	1	10	**47.4**	15.61	46.5	0.8	3
São Tomé e Príncipe	**São Tomé**	**October 2002**	***Schistometopum thomense***	4	**0.32**	0.23	0.298	0.017	2	8	**256.1**	112.61	255.0	1.2	2
Guatemala	**Quetzeltenango**	**August 2002**	***Dermophis mexicanus***	1	**0.00**		0.000	0.067	1	1	**200.0**		200.0	0.0	1
India	**Kerala**	**June 2002**	***Gegeneophis ramaswamii***	3	**0.84**	0.52	0.800	0.044	2	0					
South Africa	**Ndumu**	**January 2004**	***Zygaspis vandami***	1	**0.13**		0.133	0.000	2	7	**326.6**	210.78	324.3	2.4	1
	Kruger	**January 2004**	***Zygaspis vandami***	0							**0.0**	0.00	0.0	0.0	0

presence and abundance of dedicated subterranean burrowers. Care would have to be taken that if quadrats are nested, they are not disturbed prior to digging. The use of randomised plots and their spatial relations is strongly encouraged to enable further analysis on patch dynamics.

5. Conclusion

This study demonstrates the need for a consensus on techniques of surveying the biodiversity of soil herpetofauna. This fauna comprises of at least 2775 species (Table 1) and can be found at considerable densities (Table 2). Many species are known from only a few individuals, and the overall biodiversity of this group is certainly underestimated with respect to other terrestrial herpetofauna, both due to the superficial similarity of many species (Fig. 1), as well as their cryptic lifestyles. Like soil macrofauna [29], the majority of species appear to live within the first few centimetres of leaf litter and soil. This suggests that a two tier approach may be most appropriate. It is hoped that this contribution will stimulate further discussion towards a consensus filling the gap for a standard method of quantitative surveying of soil herpetofauna biodiversity.

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