Hand searching versus pitfall trapping: how to assess biodiversity of ground beetles (Coleoptera: Carabidae) in high altitude equatorial Andes?

Mauro Gobbi, Álvaro Barragán, Mattia Brambilla, Emilia Moreno, Washington Pruna & Pierre Moret

Journal of Insect Conservation
An international journal devoted to the conservation of insects and related invertebrates

ISSN 1366-638X
Volume 22
Combined 3-4

J Insect Conserv (2018) 22:533-543
DOI 10.1007/s10841-018-0082-8

Springer

Journal of Insect Conservation (2018) 22:533–543
https://doi.org/10.1007/s10841-018-0082-8

ORIGINAL PAPER

Hand searching versus pitfall trapping: how to assess biodiversity of ground beetles (Coleoptera: Carabidae) in high altitude equatorial Andes?

Mauro Gobbi[1] · Álvaro Barragán[2] · Mattia Brambilla[3,4] · Emilia Moreno[2] · Washington Pruna[2] · Pierre Moret[5]

Received: 10 February 2018 / Accepted: 11 August 2018 / Published online: 14 August 2018

Abstract

The use of ground beetles (Coleoptera: Carabidae) as bioindicators of environmental change depends on the reliability and the effectiveness of the sampling methods. Those that have been tested in the temperate zone and in tropical forests still await experimentation in tropical high-altitude environments. For the first time, pitfall trapping and hand searching have been compared in Ecuadorian páramo above 4000 m a.s.l., in terms of practical effectiveness. The study was performed on six volcanoes and was based on the comparison of 28 sampling sessions (pitfall trapping and hand searching) performed along two different elevational belts [lower superpáramo (LSP) and upper superpáramo (USP)]. Analyses of sampling sessions showed that detected species richness is slightly higher with hand searching than with pitfall trapping, regardless of the elevation. Additionally, hand searching is more time-effective than pitfall trapping. The performance of the sampling method slightly varies when species assemblage composition is analysed in relation to elevational belts. In the LSP, hand searching and pitfall trapping should be simultaneously used to obtain exhaustive inventories of carabid biodiversity, since different species are likely to be collected by each method. In the USP, hand searching and pitfall trapping efficiency is very similar, but hand searching allows to collect a slightly larger number of species. Lastly, the sample-based rarefaction curves showed that four temporal replicates are mandatory to obtain a robust dataset and an exhaustive inventory of the true species richness and species assemblages composition. Our findings suggest a combined use of hand searching and pitfall trapping in the LSP, while both methods can be used alone for surveying carabids in the USP. Furthermore, hand searching is recommended if the aim is to obtain an inventory of species diversity, whereas pitfall trapping seems more convenient for fine grain ecological and comparative studies.

Keywords Ecuador · Harsh environments · Páramo · Sampling effort · Sampling methods · Species richness

Introduction

Ground beetles (Coleoptera, Carabidae) have been widely used as bioindicators for monitoring habitat disturbance (e.g. Rainio and Niemelä 2003; Koivula 2011) or as early-warning indicators of the effect of environmental changes triggered by global warming, especially in mountains (e.g.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10841-018-0082-8) contains supplementary material, which is available to authorized users.

✉ Pierre Moret
pierre.moret@univ-tlse2.fr

1 Section of Invertebrate Zoology and Hydrobiology, MUSE - Museo delle Scienze, Corso del Lavoro e della Scienza 3, 38123 Trento, Italy

2 Museo de Zoología QCAZ, Escuela de Ciencias Biológicas, Pontificia Universidad Católica del Ecuador, Quito, Ecuador

3 Section of Vertebrate Zoology, MUSE - Museo delle Scienze, Corso del Lavoro e della Scienza 3, 38123 Trento, Italy

4 Settore Biodiversità e Aree Protette, Fondazione Lombardia per l'Ambiente, Largo 10 Luglio 1976 1, 20822 Seveso, Italy

5 Laboratoire TRACES UMR5608, Toulouse University, CNRS, UT2J, Toulouse, France

Bässler et al. 2013; Brambilla and Gobbi 2014; Pizzolotto et al. 2014). Most of these studies are based on pitfall trapping (Skvarla et al. 2016). This widespread and standard method has the advantage of being cheap, easy to implement and suitable for quantitative comparison, but it also has the drawback of reflecting activity rates rather than absolute density or actual assemblage composition (Spence and Niemelä 1994; Kotze et al. 2011). The few studies that have addressed direct comparisons between pitfall trapping and other sampling methods such as quadrat sampling, litter washing, suction sampling or nocturnal hand searching at lights, were all performed in temperate or boreal regions of Eurasia and North America (Spence and Niemelä 1994; Andersen 1995; Lin et al. 2005; Liu et al. 2007; Hancock and Legg 2012; Zhao et al. 2013; Andersen and Arneberg 2016).

Pitfall trapping has been tested in tropical regions, with results suggesting that it is less efficient than hand searching in lowlands and in montane forests (Rainio and Niemelä 2006; Nyundo and Yarro 2007; Maveety et al. 2011), but no study has been carried out in the tropical alpine ecosystem, above the treeline, to measure or compare performances of sampling methods. Yet Carabid beetles are one of the most important components of the ground-dwelling macroinvertebrate assemblages of this high-altitude ecosystem, called páramo in tropical Andes of Venezuela, Colombia, Ecuador and Northern Perú (Moret 2009). Moreover, it has been shown that this beetle family is able to provide accurate information on the response of high-altitude insect communities to the ongoing climate change (Moret et al. 2016). The selection of the most appropriate sampling method for the tropical alpine ecosystem is therefore a crucial issue that needs to be addressed from two points of view: adequacy to the requirements of a quantitative analysis aimed to future long-term biodiversity monitoring surveys, and practical effectiveness under the constraints of a harsh environment.

Regarding the first point, the sampling protocol must follow a standardized framework and consider an appropriate number of replicates, and must be suitable for a simultaneous implementation in different habitats along elevational gradients and for replicates at the same place at regular intervals (Kotze et al. 2011; Schweiger et al. 2016). Regarding environmental constraints, the demanding conditions of high altitude environments in terms of accessibility of often remote mountains, weather instability and physical effort, require a sampling method that is as easy as possible to carry out, with regard to time-effectiveness and labour intensity. Quadrat sampling of the whole Carabid assemblage in each sampling site, both on the ground and in the superficial layer of the soil (Hansson 2012), must be discarded, as it would be extremely difficult in steep rocky environments. Moreover, a complete destruction of the vegetation cover would not be acceptable in a fragile ecosystem where the resumption of vegetation is extremely slow. On the other hand, an experiment comparing suction sampling and pitfall trapping in steep alpine habitats of Austria, between 1950 and 2300 m a.s.l., showed that suction sampling resulted in a very low representation of Carabids, and was more expensive and time consuming (Bergthaler and Relys 2002). Therefore, our study only focuses on the comparison of two methods: pitfall trapping and time-limited hand searching.

The aims of our study were thus (1) to test the performance of hand searching and pitfall trapping in the highest zone of the páramo in terms of species richness and species assemblage similarities, and (2) to test how many sampling sessions of hand searching and pitfall trapping should be performed in sites located in the lower superpáramo (LSP) as well as in the upper superpáramo (USP), in order to obtain an inventory, as much as possible complete, of the species diversity.

Materials and methods

Study area

The study was performed in the Andes of Northern Ecuador (Fig. 1a), in six isolated high-altitude island-like habitats (Anthelme et al. 2014) that are distributed on three volcanoes of the Western Cordillera (from north to south, Chiles, Pichincha and Carihuairazo) and three volcanoes of the Eastern Cordillera (Cayambe, Guamaní and Antisana). The selected volcanoes reflect the whole diversity range of high altitude environments in Ecuador, in terms of geological age of volcanic formations, microclimate and extension of the glaciers.

All study sites belong to the superpáramo belt that replaces grassland páramo above a line that varies between 4100 and 4300 m a.s.l., depending on local abiotic conditions. Superpáramo is characterized by sclerophyllous shrubs, cushion plants and shortstem grasses, with a vegetation cover that decreases with elevation (Sklenár and Balslev 2005). From 4200/4300 m to 4400/4500 m, the LSP is richer in plant species and has a vegetation cover of at least 50% (Fig. 1b). Above 4400/4500 m, the USP has a low and patchy vegetation cover, frequently < 20%, confined to a few favourable habitats and dominated by cushion plants and short stem grasses (Fig. 1b, c).

Sampling methods

Hand searching Ground beetles were searched by hand, beneath stones and any other hiding places, without tearing live plants, in areas presenting a homogenous habitat type, by three experienced collectors during fixed periods of 15 min

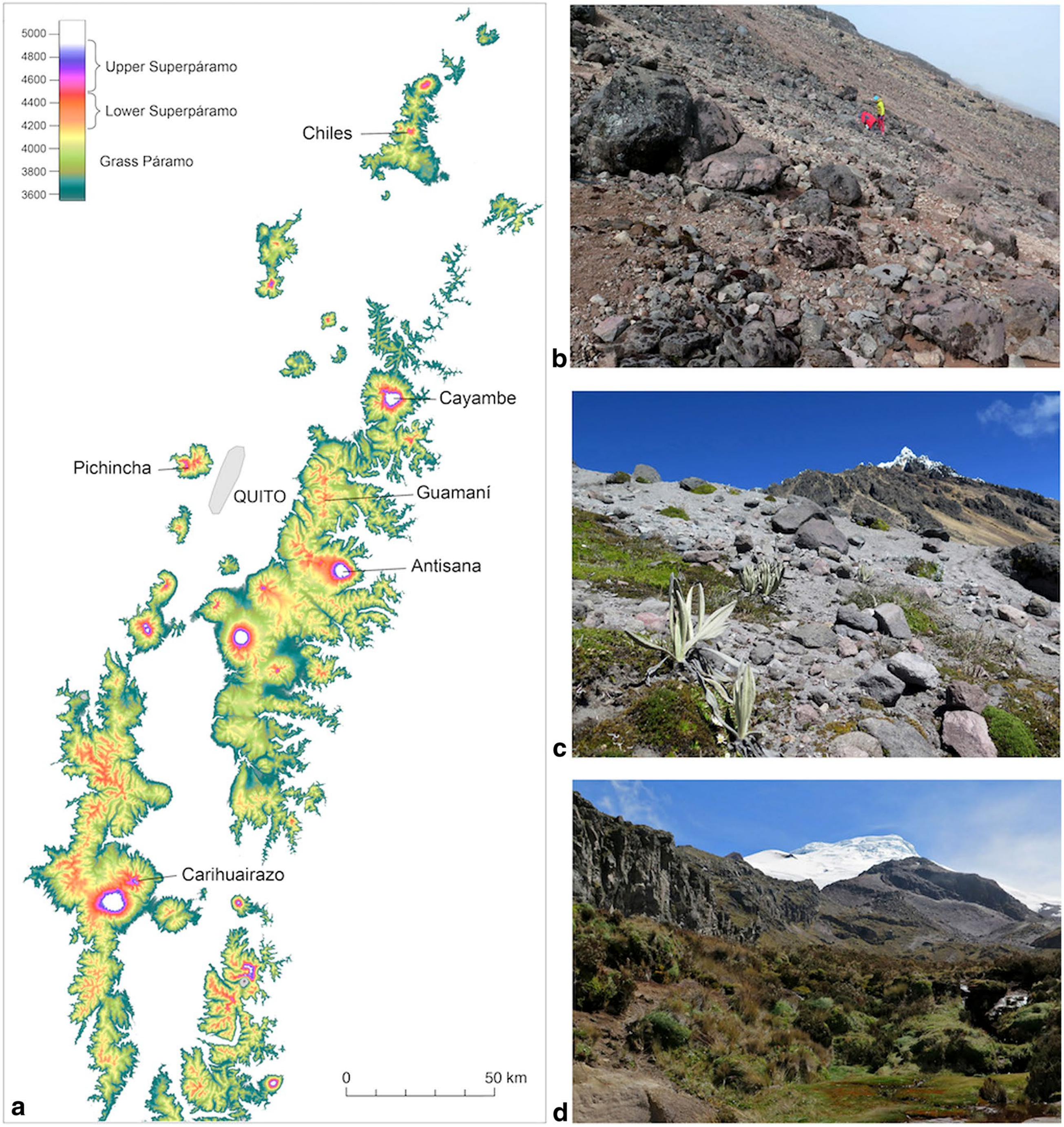

Fig. 1 **a** Map of the páramo ecosystem in the Northern part of Ecuadorian Andes, and localisation of the six volcanoes considered to test the performance of hand searching and pitfall trapping in LSP and USP in terms of species richness and species assemblage similarities. **b** Desert USP on Volcano Chiles at 4510 m. **c** USP on Volcano Illiniza at 4530 m. **d** LSP on Volcano Cayambe at 4390 m

(Chiles, Pichincha, Cayambe, Guamaní, Carihuairazo) or by two experienced collectors for 20 min (Antisana).

Pitfall traps Each trap consists in a plastic cup (7 cm of upper diameter) containing 2/3 standard mixture of wine vinegar, salt and a few drops of soap (Gobbi et al. 2006). Each trap was covered with a plastic dish located about 3 cm above the trap in order to limit the access of rain water; in addition, a small hole was made approximately 1/3 of the way down the cup to allow excess rain water to drain away (Brandmayr et al. 2005). The number of traps used at each site varied between 3 and 8 in relation to the local microhabitat heterogeneity and extension. Traps were collected and re-set after an average period of 10 days.

At each study site, sampling sessions were scheduled so that pitfall traps were collected and hand searching was done on the same day, thus ensuring similar weather and seasonal conditions for the results of both methods.

Identifications were made to the species level, following the taxonomic arrangement proposed by Moret (2005). All specimens were preserved in 70% ethanol and deposited in the insect collection of the QCAZ Zoology Museum at the Pontificia Universidad Católica del Ecuador (Quito, Ecuador).

Data analysis

Hand searching versus pitfall trapping in two different elevational belts

We considered data collected for 3 years, 2015–2016–2017, on six volcanoes (Chiles, Guamaní, Cayambe, Pichincha, Antisana, Carihuairazo) for testing the effectiveness of hand searching and pitfall trapping to collect carabids respectively in the LSP and USP (see Suppl. File). Data from all volcanoes were merged to obtain a dataset with 28 sampling sessions.

N-mixture models (Royle 2004) were used to evaluate whether the two methods provide consistent results about species richness and to estimate the degree of precision of the estimates provided. This analysis was carried considering the species richness obtained in the 28 sampling sessions adopting hand searching and pitfall trapping, using the package 'unmarked' (Fiske and Chandler 2011) and 'MuMIn' (Bartoń 2016) in R (R Core Team 2016). We first fitted a model relating species richness to the method used (hand searching vs. pitfall trapping) as a factor affecting detection (observation covariate), and to elevation as a factor affecting true species richness (site covariate). Then, we ranked all possible models (method, elevation, method + elevation) according to the relative value of the Akaike's Information Criterion corrected for small sample size (AICc) and identified the most supported models (ΔAICc < 2) after the exclusion of uninformative parameters (Arnold 2010; Jedlikowski et al. 2016). Finally, we estimated the latent abundance by means of the 'ranef' command in 'unmarked', which provides an estimate posterior distribution of the latent richness according to empirical Bayesian methods (Royle and Dorazio 2008).

The difference in species assemblages sampled by hand searching and pitfall trapping respectively in the LSP and USP was discriminated by non-metric multidimensional scaling (NMDS). The Jaccard index, for presence/absence data, were used to measure similarity between samples. The NMDS goodness of fit was estimated with a stress function, which ranges from 0 to 1, with values close to 0 indicating good fit. Then, we performed an analysis of similarities (ANOSIM) based on Jaccard index to test the significance of the similarities and to evaluate the degree of separation between species assemblages (Hammer et al. 2001; Gotelli and Ellison 2004).

Number of required sampling sessions

From the six volcanoes under study, three (Pichincha, Antisana, Carihuairazo) were selected to evaluate how many sampling sessions are necessary to obtain an inventory, as complete as possible, of the species living at a given elevation. On each volcano we selected two sampling sites, one in LSP and the other in USP, to test if the number of required sampling sessions changes in relation to the altitudinal belt. Three (Carihuairazo) or four (Pichincha, Antisana) sampling sessions were performed at each sampling site (see Table 1).

Firstly, the observed species richness (count data) and the estimated species richness (incidence-based non-parametric diversity estimator) were compared for both sampling methods in each altitudinal belt. The incidence coverage estimator (ICE) was used to estimate potential true richness; ICE estimates the overall number of species that may live at one site, based on the observed number of species and the frequency of their occurrence, and it gives accurate results in surveys performed by hand searching and pitfall traps (Hortal et al. 2006; Colwell 2013).

Then, we used the species accumulation curves, as a standard method to measure the completeness of the surveys performed by hand searching and pitfall trapping and to allow comparison between surveys. Specifically, we calculated a Mau-Tau sample-based rarefaction species accumulation curve "S(est)" (Colwell 2013) for each sampling technique used respectively in the LSP and USP sites on each volcano.

We used the statistical software EstimateS 9.1.0 (Colwell 2013) and PAST 3.16 (Hammer et al. 2001) to perform these analyses.

Results

Hand searching versus pitfall trapping in two different elevational belts

The general analysis based on N-mixture modelling identified a single model, including only the method used, as the most supported one; all other models after the exclusion of the uninformative parameters had ΔAICc > 2. This model (intercept: 0.46 ± 0.63) suggested that the detected species richness was only affected by the method adopted, with pitfall trapping resulting in lower estimates of richness

Table 1 Sampling data used to test how many hand searching (HS) and pitfall trapping (PFT) replicates should be performed to obtain an exhaustive inventory of species diversity, in the LSP and in the USP; number of sampled and estimated (ICE) species of carabids collected by HS and PFT respectively in the LSP and USP

Volcano	Sampling site	Elevational belt	Sampling technique	Replicated sampling sessions	Sampling dates	Sampling effort	Sampled individuals	Sampled species	Estimated species number (ICE)	Total sampled species (HS+PFT)
Pichincha	P2 4570 m	LSP	HS	4	12.III.2015/17.IX.2015/22, 29.X.2016	30 min (3 operators)	719	8	9	9
			PFT	4	III.2016/23, 29.X.2016/18.VI.2017	10 days (6 traps)	276	8	9	
	P3 4650 m	USP	HS	4	12.III.2015/17.IX.2015/22, 29.X.2016	30 min (3 operators)	203	8	9	8
			PFT	4	III.2016/23, 29.X.2016/18.VI.2017	10 days (6 traps)	565	7	8	
Antisana	A1 4400 m	LSP	HS	4	15, 23, 29.X.2016/18.VI.2017	20 min (2 operators)	180	8	9	13
			PFT	4	IV.2016/23, 29.X.2016/18.VI.2017	8 days (8 traps)	98	7	8	
	A3 4700 m	USP	HS	4	15, 23, 29.X.2016/18.VI.2017	20 min (2 operators)	181	11	12	13
			PFT	4	IV.2016/23, 29.X.2016/18.VI.2017	8 days (8 traps)	556	10	12	
Carihuairazo	CR1 4270 m	LSP	HS	3	26.XI.2016/10, 22.XII.2016	15 min (3 operators)	171	4	4	6
			PFT	3	10, 22.XII. 2016/21.III.2017	14 days (6 traps)	39	6	6	
	CR2 4640 m	USP	HS	3	26.XI.2016/10, 22.XII.2016	15 min (3 operators)	131	6	10	8
			PFT	3	10, 22.XII. 2016/21.III.2017	14 days (6 traps)	536	6	6	

(−0.55 ± 0.25, Z = −2.23, P = 0.026) (Fig. 2). The latent species richness as estimated by the model varied between 6 and 14 species per site (modal value), with 2.5–97.5% credible intervals between 3 and 19 (range of detected values: 2–9 with hand searching, 0–7 with pitfall trapping) (Fig. 2). The mean value of latent species richness was highly correlated with the total number of species sampled during a session (r = 0.87, P < 0.001).

In the LSP, NMDS revealed differences in carabid community composition (stress = 0.39) in relation to the sampling method; ANOSIM significantly separated the two collection methods (P = 0.005), but the effect of the sampling methods is small (r = 0.12) (Fig. 3a). The same result was obtained after removing the singleton species collected by each sampling method (6 species by HS, 6 species by PFT): NMDS stress = 0.39; ANOSIM r = 0.12, P = 0.009.

In the USP, no significant changes were found between collections made by hand searching and by pitfall trapping. NMDS did not reveal differences in carabid community composition between both collection methods (stress = 0.31); ANOSIM did not significantly separate the two collection methods (ANOSIM, r = −0.06, P = 0.94) (Fig. 3b). The same result was obtained after removing the singleton species collected by each sampling method (1 species by HS, 5 species by PFT): NMDS stress = 0.31; ANOSIM r = −0.06, P = 0.89.

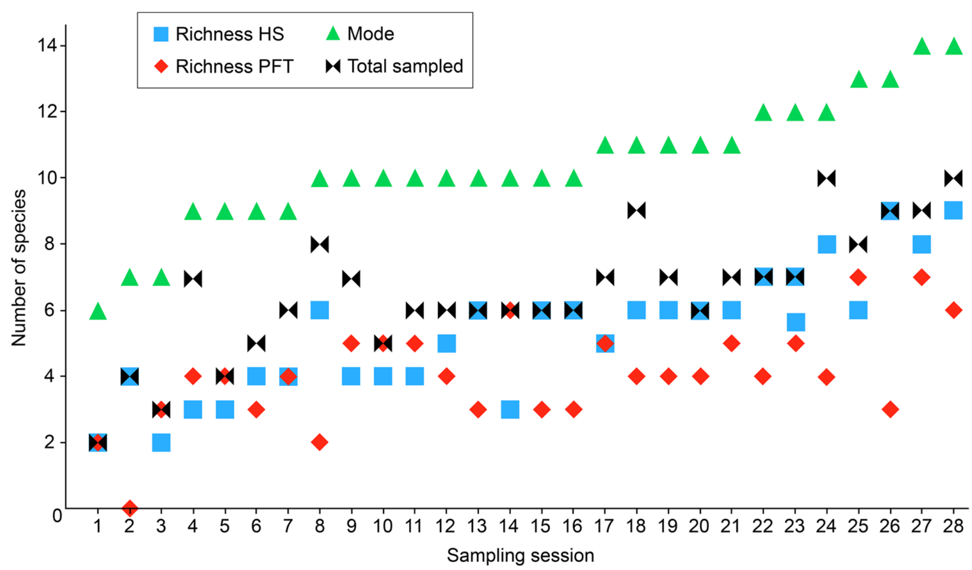

Fig. 2 Number of species sampled by means of hand searching ("richness HS") and pitfall trapping ("richness PFT"). The overall number of collected species ("total sampled") and the estimated richness (modal value) according to the selected N-mixture model "Mode" are also shown

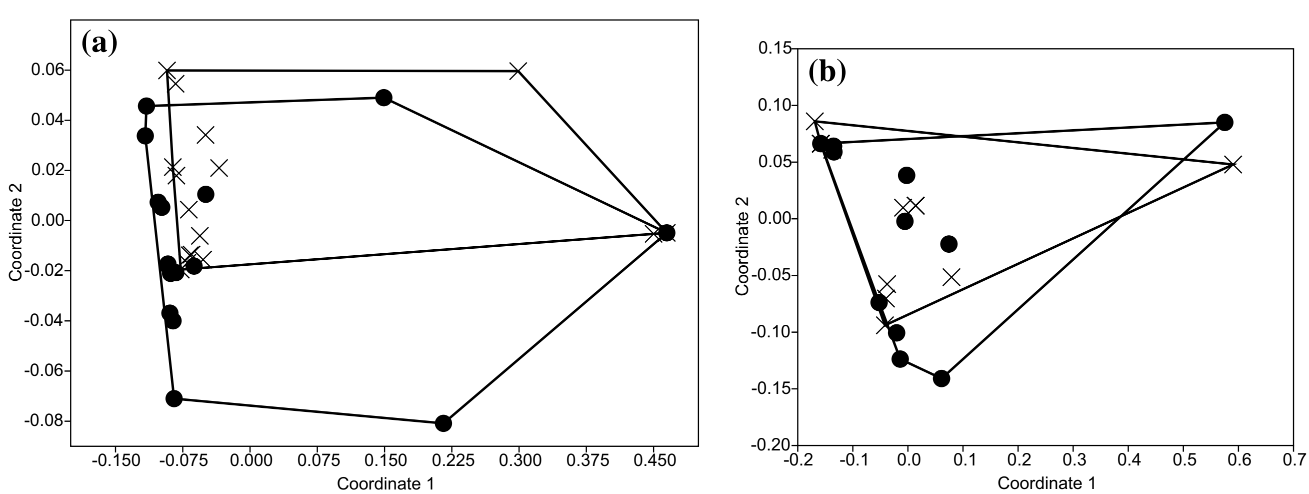

Fig. 3 NMDS analysis of the different subset of carabid community sampled by hand searching (X) and pitfall trapping (black dots) in the LSP (**a**) and in the USP (**b**)

Number of required sampling sessions

On Pichincha the species richness estimators did not show different results between the sampling methods because the number of sampled species is very near to the number of expected species for either method and in either altitudinal belt (Table 1). On Antisana, results are different in LSP and in USP. In the USP, similarly to what has been observed on the Pichincha, the species richness estimators give the same result for both sampling methods, for the same reason (Table 1). In the LSP, the total number of species collected by hand searching plus pitfall trapping is significantly higher than the number of species collected or estimated using either sampling method.

On Pichincha and Antisana, the accumulation curves computed for hand searching and pitfall trapping both in the LSP and the USP showed very similar trends and suggested that four sampling sessions ensure to collect about 90% of the expected species (Fig. 4). However, on Antisana the whole number of species sampled by hand searching plus pitfall trapping is higher than the value estimated separately for each sampling method, which means that the assemblages collected by means of each sampling method are different.

On Carihuairazo, three sampling sessions performed in LSP by pitfall trapping allowed to collect 100% of the estimated species number, whereas in the same elevational belt and with the same number of sampling sessions, hand searching allowed to collect only 75% of the estimated species richness. In USP three sampling sessions did not ensure to obtain an exhaustive view of the true species richness since <75% of the estimated species were collected (Table 1; Fig. 3).

Discussion

Hand searching versus pitfall trapping: general pattern

In the analysis focused on sampling sessions, carried out within an occupancy-model framework, hand searching was suggested to be slightly but significantly better performing than pitfall trapping. Our analysis based on N-mixture modelling should be treated with caution, considering the limited sample size, which prevented us to test the effect of other factors potentially affecting the species richness detected at a given site, such as site-specific habitat features or specific detailed assessments of field effort. Nevertheless, the results provided by this analysis are coherent with those highlighted by site-specific and method-specific ICE estimates, and approached well the total number of species sampled at a given site using both methods: the estimated richness per sampling session was strongly related to the total richness sampled during that session ($r = 0.87$, $P < 0.001$), with a difference between the estimated modal value and the total number of species sampled in that site never larger than five. This suggests that our inference about the different effect of the sampling method could be taken as a meaningful indication, despite the low sample size.

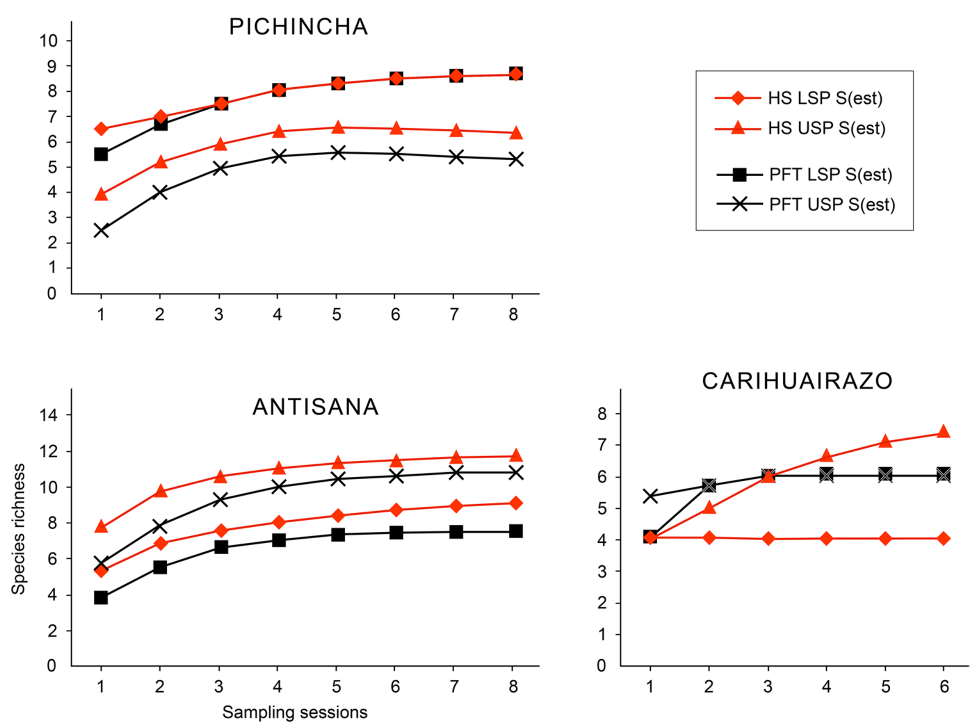

Fig. 4 Sample-based rarefaction curves for HS and PFT on sites located in the LSP and in the USP

Hand searching and pitfall trapping operate quite differently: the former is an active and time-limited method performed during the day, when páramo carabids are inactive in their shelters, whereas the latter is a passive method, which collects carabids during the night, when they are active. The good performance of hand searching is an unexpected result, as according to recent literature, several drawbacks are associated with this method: as any active method, it partly depends on the individual skill and experience of the collectors; it can alter or destroy habitats; it does not offer reliable means of standardization; it can lead to low numbers of individuals per species (Bouget et al. 2008; Riley et al. 2016). Therefore, hand searching was not considered capable of replacing pitfall trapping, which has been universally accepted in temperate regions as the most efficient sampling method for the time and effort used (Spence and Niemelä 1994; Skvarla et al. 2016). Other methods have been tested, such as exhaustive hand searching in quadrat plots (Andersen 1995; Lin et al. 2005; Andersen and Arneberg 2016), but they are not commonly implemented because the slight benefits they possibly bring in terms of quantitative accuracy do not offset their high cost in terms of invested time and labour intensity.

The simpler and far more time-effective hand searching method we used in this study, which is time-limited but not intended to exhaustively collect every carabid beetle present on the ground or in the upper soil layer within a delimited quadrat, has never been tested in temperate regions. In tropical highlands, our study showed that it did not underestimate carabid species richness in comparison with pitfall trapping, and that his performance was even slightly better. The effectiveness of hand searching in the páramo environment may be due to the low diversity of microhabitats suitable for carabids. There is no deep vegetal litter, no decaying wood elements, but many stones resting on the soil, under which large numbers of carabids use to hide during the day. So, hand searching beneath these stones is an easy task that greatly reduces the abovementioned flaws. The shelter can be put back in place without destroying the biotope; a quick training allows even a novice collector to sample as much insects as an experienced one; and the size of the samples is sufficient to carry out quantitative analyses.

On the other hand, though slightly less effective, pitfall trapping still constitutes a valuable sampling method in the páramo ecosystem. This result differs from what has been observed in other tropical ecosystems. Hand searching allowed to collect much more individuals and species than pitfall trapping in lowland rain forest of Ecuador (Riley et al. 2016) and in montane rain forests of Madagascar (Rainio and Niemelä 2006) and Tanzania (Nyundo and Yarro 2007). A survey along an elevational transect in high montane forest of south-eastern Perú, from 1400 to 3400 m a.s.l., combining hand searching and pitfall trapping at every spot, showed that hand searching yielded three times more individuals and twice as many species than pitfall traps (Maveety et al. 2011). All these studies were performed at lower elevations, in tropical ecosystems where a high percentage of carabid species are arboreal (Erwin 1991; Paarmann et al. 2001), which is obviously the main reason of the low performance of pitfall trapping. On the contrary, due to the absence of arboreal habitats, all páramo carabids live on the ground and are likely to be captured by means of pitfall traps.

Regarding cost and time effectiveness, hand searching and pitfall trapping are equally cheap, as they do not need any expensive equipment. However, pitfall trapping is significantly more time consuming since it needs one more field trip to install the traps. The extra effort therefore amounts to 25% in case of three sessions, or to 20% in case of four sessions. From this point of view, hand searching would be more suitable for quick and cheap surveys.

Differences across elevational belts

Regarding species assemblage composition, elevation seems to partially drive the capability of the sampling methods to collect the same species assemblages. The multivariate analysis showed that in the LSP carabid species assemblages collected by hand searching are slightly different from those collected by pitfall trapping, while in the USP they are very similar. We obtained the same result both considering the overall sampled species and after removing the very rare species (singleton species). A possible explanation must be sought in the capability of each sampling method. Hand searching performances are mainly conditioned by: (1) the skill of the collector; (2) the accessibility of the microhabitats where ground beetles are likely to hide during the day. Pitfall trapping efficiency is determined by (1) the trapping design, in terms of size, form, material of the traps, their layout and the preservative mixture that is used (review in Skvarla et al. 2016), (2) the weather conditions during the activity period of the traps, especially at high altitudes where a period of bad weather can dramatically reduce the activity of nocturnal open ground predators, and (3) the activity rate of each species. In the USP, vegetation is scarce and the soil layer is thin; every possible hiding place is easy to find and to inspect (Fig. 1b, c). In the LSP, a thicker and denser vegetation cover, along with a deeper soil layer, makes it impossible to inspect every possible microhabitat by hand searching, especially beneath the cushion plants that cover large parts of the ground, or amid the dead leave litter at the base of other plants (Fig. 1d).

Therefore, in the LSP the simultaneous use of hand searching and pitfall trapping is strongly recommended in order to obtain a complete inventory of the species living there. In the USP it is possible to use only one sampling method, and in this case hand searching should be preferred because it is able to collect a slightly larger number of species and it demands less sampling effort than pitfall trapping, as the latter requires an extra field trip for the same number of samples. Moreover, in the fragile environment of USP, hand searching does not entail the risk of decimating small endangered populations, as it could happen with an oversized pitfall layout. On the other hand, a possible weakness of this approach is that, differently to hand searching, pitfall trapping is a semi-quantitative and standardised sampling method that has been widely used in temperate habitats sensitive to the climate change, like those near the glaciers front, both at high latitudes (e.g. Norway, Bråten et al. 2012; Vater and Matthews 2015) and high altitudes (e.g. Alps, Tampucci et al. 2015; Pizzolotto et al. 2016; Gobbi et al. 2017). Thus, using such a commonly shared sampling method would allow to obtain statistically comparable data from all over the world.

Number of required sampling sessions

The rarefaction curves and richness estimator performed on three of the six selected volcanoes suggested that four sampling sessions (temporal replicates) are enough to obtain a realistic inventory of the species richness both considering hand searching and pitfall trapping. In other words, after four sampling sessions the observed specie richness is very near to the estimated species richness. This result is in agreement with similar studies in high altitude habitats of the Alps (Gobbi et al. 2007; Tampucci et al. 2015).

On the other hand, the estimated number of species sampled by each method is often lower than the number of species collected merging both of them. This result can be explained considering the abovementioned bias: in the LSP each sampling method collects different species assemblages. Incomplete sampling is a result that has been discussed in several studies on arthropods of tropical forests, due to the high micro-habitat diversity and consequently the high species diversity and the high number of rare species (Lucky et al. 2002; Riley et al. 2016). In the Ecuadorian lowland rain forest, seven hand sampling events only allowed to collect 54–61% of the potential species richness of the area (Riley et al. 2016). Our results indicate that a complete survey of species diversity is more easily reached in high altitude tropical habitats, with only four sampling sessions. However, the required sampling effort is still twice more time consuming in the Ecuadorian páramo than in temperate alpine habitats, as it has been reported that only two sampling sessions are enough in the Alps to get an exhaustive view of the species assemblages (Harry et al. 2011).

Conclusions

The results of this study show that, unlike in other tropical environments, pitfall trapping in the high altitude páramo ecosystem gives rather reliable account for Carabid diversity, with sampling results that are very similar to those obtained by means of hand searching (as far as species richness is the target), even though, within a single session, hand searching generally allows to find a slightly larger number of species. Importantly, the species assemblages obtained by both methods are slightly different, especially in the LSP, due to biases that would deserve more specific investigation. Based on these results, the following recommendations can be given: (a) In the more diverse habitat of LSP, hand searching and pitfall trapping should be simultaneously used to obtain robust inventories of carabid biodiversity; (b) in the simpler habitat of USP, any one of the two methods can be used alone for surveying carabids, yet hand searching can be recommended if the aim is only to obtain an inventory of species diversity, while pitfall trapping seems more convenient for fine grain ecological studies; (c) in both superpáramo belts, either method requires four temporal replicates for obtaining a robust dataset and a consistent inventory of the true species richness and of the species assemblage composition.

This study is especially useful in view of a long-term survey of carabid diversity, taking this beetle family as a bioindicator of the impact of climate change on high altitude arthropod communities, since our results demonstrate that such a survey can be implemented in tropical mountains with a cheap and time-effective sampling design. The results obtained in the Andes of Ecuador are likely to have a wide application in other tropical mountains, and may provide guidance for sampling other ground-dwelling arthropods (e.g. spiders) with similar life style and behaviour.

Acknowledgements This study is part of the SUMMITEX project funded by the CNRS (PICS-06724, 2015–2017 and MSHS-T USR 3414), the INSPYRAND project funded by the CNRS (PEPS 2016, INSHS and Réseau National des MSH), and three PUCE projects (2016–2017): *Influencia de la altitud en comunidades de insectos de importancia forense*, code N13456A, *Efecto del rápido retroceso glaciar sobre la biodiversidad en ecosistemas tropicales de altura*, code M13434, and *Monitoring Climate Change Impact on the High Andes* (MICCAA), code N13419. The Ecuadorian Ministerio de Ambiente provided research and collection Permits Numbers 005-12-IC-FAU-DNB/MA, 003-15-IC-FAU-DNB/MA, 005-14-IC-FAU-DNB/MA and 005-15-IC-FAU-DNB/MA. Mauro Gobbi's field trip to Ecuadorian Andes was co-funded by CNRS and Autonomous Province of Trento (Italy), patronage by Club Alpino Italiano (Sezione Val Comelico) and supported by the technical sponsor GM Calze srl. Special thanks are due to Saúl Aguirre, María de los Ángeles Aráuz, Esteban Bastidas, Verónica Crespo for their help during the field work, and to Ricardo Jaramillo and Priscilla Muriel for the funding, logistic, administrative and data management support on the Antisana site. The fieldtrip was also funded by grants from Secretaría de Educación Superior, Ciencia, Tecnología e Innovación (SENESCYT, Arca de Noé Initiative; S. R. Ron and O. Torres-Carvajal Principal Investigators).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Andersen J (1995) A comparison of pitfall trapping and quadrat sampling of Carabidae (Coleoptera) on river banks. Entomol Fenn 6:65–77

Andersen J, Arneberg P (2016) Hand collection as a method for assessing the community structure of carabid beetles. Pedobiologia 59(3):73–81

Anthelme F, Jacobsen D, Macek P, Meneses RI, Moret P, Beck S, Dangles O (2014) Biodiversity patterns and continental insularity in the tropical high-Andes. Arct Antarct Al Res 46:811–828

Arnold TW (2010) Uninformative parameters and model selection using Akaike's information criterion. J Wildl Manag 74:1175–1178

Bartoń K (2016) MuMIn: Multi-Model Inference. R package version 1.15.6

Bässler C, Hothorn T, Brandl R, Müller J (2013) Insects overshoot the expected upslope shift caused by climate warming. PLoS ONE 8:e65842. https://doi.org/10.1371/journal.pone.0065842

Bergthaler GJ, Relys V (2002) Suction sampling in alpine habitats: experiences and suggestions. In: Toft S, Scharff N (eds) European arachnology 2000. Aarhus University Press, Aarhus, pp 291–297

Bouget C, Brustel H, Brin A, Noblecourt T (2008) Sampling saproxylic beetles with window flight traps: methodological insights. Rev Écol (Terre Vie) 10:21–32

Brambilla M, Gobbi M (2014) A century of chasing the ice: delayed colonisation of ice-free sites by ground beetles along glacier forelands in the Alps. Ecography 37(1):33–42

Brandmayr P, Zetto Brandmayr T, Pizzolotto R (2005) I Coleotteri Carabidi per la valutazione ambientale e la conservazione delle biodiversità. Manuale operativo, vol 34. Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici, IGER, Roma

Bråten AT, Flø D, Hågvar S, Hanssen O, Mong CE, Aakra K (2012) Primary succession of surface active beetles and spiders in an alpine glacier foreland, central south Norway. Arct Antarct Alp Res 44(1):2–15

Colwell RK (2013) EstimateS: Statistical estimation of species richness and shared species from samples [computer program]. Version 9.1.0. http://viceroy.eeb.uconn.edu/estimates/index.html. Accessed 23 Oct 2017

Erwin TL (1991) Natural history of the carabid beetles at the BIOLAT Biological Station, Rio Manu, Pakitza, Peru. Rev Peru Entomol 33:1–85

Fiske IJ, Chandler RB (2011) Unmarked: an R package for fitting hierarchical models of wildlife occurrence and abundance. J Stat Softw 43:1–23

Gobbi M, Fontaneto D, De Bernardi F (2006) Climate impacts on animal communities in space and time: the case of spider assemblages along an alpine glacier foreland. Glob Change Biol 12:1985–1992

Gobbi M, Rossaro B, Vater A, De Bernardi F, Pelfini M, Brandmayr P (2007) Environmental features influencing carabid beetle (Coleoptera) assemblages along a recently ice-free area in the Alpine region. Ecol Entomol 32:682–689

Gobbi M, Ballarin F, Brambilla M, Compostella C, Isaia M, Losapio G, Maffioletti C, Seppi R, Tampucci D, Caccianiga M (2017) Life in harsh environments: carabid and spider trait types and functional diversity on a debris-covered glacier and along its foreland. Ecol Entomol 42:838–848

Gotelli NJ, Ellison AM (2004) A primer of ecological statistics. Sinauer Associates, Sunderland

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica 4:9 (**Version 3.16**)

Hancock MH, Legg CJ (2012) Pitfall trapping bias and arthropod body mass. Insect Conser Diver 5(4):312–318

Hansson I (2012) Ecological principles of nature conservation application in temperate and boreal environments. Springer, Berlin

Harry I, Drees C, Höfer H, Assmann T (2011) When to sample in an inaccessible landscape: a case study with carabids from the Allgäu (Northern Alps) (Coleoptera, Carabidae). ZooKeys. https://doi.org/10.3897/zookeys.100.1531

Hortal J, Borges PAV, Gaspar C (2006) Evaluating the performance of species richness estimators: sensitivity to sample grain size. J Anim Ecol 75:274–287

Jedlikowski J, Chibowski P, Karasek T, Brambilla M (2016) Multi-scale habitat selection in highly territorial bird species: exploring the contribution of nest, territory and landscape levels to site choice in breeding rallids (Aves: Rallidae). Acta Oecol 73:10–20

Koivula MJ (2011) Useful model organisms, indicators, or both? Ground beetles (Coleoptera, Carabidae) reflecting environmental conditions. ZooKeys 100:287–317

Kotze D, Brandmayr P, Casale A, Dauffy-Richard E, Dekoninck W, Koivula M, Lovei G, Mossakowski D, Noordijk J, Paarmann W, Pizzoloto R, Saska P, Schwerk A, Serrano J, Szyszko J, Taboada Palomares A, Turin H, Venn S, Vermeulen R, Zetto Brandmayr T (2011) Forty years of carabid beetle research in Europe—from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. ZooKeys 100:55–148

Lin YC, James R, Dolman PM (2005) Are pitfalls biased? A comparison of carabid composition from pitfall trapping and hand searching in forest habitats. Br J Entomol Nat Hist 18:17–25

Liu Y, Axmacher JC, Li L, Wang C, Yu Z (2007) Ground beetle (Coleoptera: Carabidae) inventories: a comparison of light and pitfall trapping. Bull Entomol Res 97(6):577–583

Lucky A, Erwin T, Witman JD (2002) Temporal and spatial diversity and distribution of arboreal Carabidae (Coleoptera) in a Western Amazonian rain forest. Biotropica 34(3):376–386

Maveety SA, Browne RA, Erwin TL (2011) Carabidae diversity along an altitudinal gradient in a Peruvian cloud forest (Coleoptera). Zookeys 147:651–666

Moret P (2005) Los coleópteros Carabidae del páramo en los Andes del Ecuador. Sistemática, ecología y biogeografía. Pontificia Universidad Católica del Ecuador, Centro de Biodiversidad y Ambiente, Monografía 2, Quito

Moret P (2009) Altitudinal distribution, diversity and endemicity of Carabidae (Coleoptera) in the páramos of Ecuadorian Andes. Annales de la Société entomologique de France (N.S.), 45:4, 500–510

Moret P, Aráuz M, Gobbi M, Barragán A (2016) Climate warming effects in the tropical Andes: first evidence for upslope shifts of Carabidae (Coleoptera) in Ecuador. Insect Conserv Divers 9:342–350

Nyundo BA, Yarro JG (2007) An assessment of methods for sampling carabid beetles (Coleoptera: Carabidae) in a montane rain forest. Tanzan J Sci 33:41–49

Paarmann W, Adis J, Stork N, Gutzmann B, Stumpe P, Staritz B, Bolte H, Kuppers S, Holzkamp K, Niers C (2001) The structure of ground beetle assemblages (Coleoptera: Carabidae) at fig fruit

falls (Moraceae) in a terra firme rain forest near Manaus (Brazil). J Trop Ecol 17(4):549–561
Pizzolotto R, Gobbi M, Brandmayr P (2014) Changes in ground beetle assemblages above and below the treeline of the dolomites after almost 30 years (1980/2009). Ecol Evol 4:1284–1294
Pizzolotto R, Alice A, Gobbi M, Brandmayr P (2016) Habitat diversity analysis along an altitudinal sequence of alpine habitats: the carabid beetle assemblages as a study model. Period Biol 118(3):241–254
R Core Team (2016) A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
Rainio J, Niemelä J (2003) Ground beetles (Coleoptera: Carabidae) as bioindicators. Biodiv Conserv 12:487–506
Rainio J, Niemelä J (2006) Comparison of carabid beetle (Coleoptera: Carabidae) occurrence in rain forest and human-modified sites in south-eastern Madagascar. J Insect Conserv 10(3):219–228
Riley KN, Browne RA, Erwin T (2016) Results from two sampling techniques for carabid beetles (Coleoptera: Carabidae) in temporarily flooded and terra firme rainforest of western Amazonia. Stud Neotrop Fauna Environ 51(1):78–95
Royle JA (2004) N-mixture models for estimating population size from spatially replicated counts. Biometrics 60:108–115
Royle JA, Dorazio RM (2008) Hierarchical modeling and inference in ecology. Academic Press, Amsterdam
Schweiger AH, Irl SDH, Steinbauer MJ, Dengler J, Beierkuhnlein C (2016) Optimizing sampling approaches along ecological gradients. Methods Ecol Evol 7:463–471. https://doi.org/10.1111/2041-210X.12495
Sklenár P, Balslev H (2005) Superpáramo plant species diversity and phytogeography in Ecuador. Flora 200:416–433
Skvarla MJ, Larson JL, Dowling APG (2016) Pitfalls and preservatives: a review. J Entomol Soc Ontario 145:15–43
Spence J, Niemelä J (1994) Sampling carabid assemblages with pitfall traps: the madness and the method. Can Entomol 126(3):881–894
Tampucci D, Gobbi M, Cabrini E, Compostella C, Marano G, Pantini P et al (2015) Plant and arthropod colonization of a glacier foreland in a peripheral mountain range. Biodiversity 16:213–223
Vater AE, Matthews JA. Succession of pitfall-trapped insects and arachnids on eight Norwegian glacier forelands along an altitudinal gradient: patterns and models. Holocene 25(1):108–129
Zhao ZH, Shi PJ, Hui C, Ouyang F, Ge F, Li BL (2013) Solving the pitfalls of pitfall trapping: a two-circle method for density estimation of ground-dwelling arthropods. Methods Ecol Evol 4:865–871