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Original Article

Pitfall Traps: A Review of Methods for Estimating Arthropod Abundance

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ABSTRACT Pitfall traps are commonly used in diet studies for insectivorous and omnivorous wildlife. Pitfall trap methodologies and designs vary considerably among studies and investigators. Such variation and lack of standardization limits scientists' abilities to compare their results with others. We conducted a literature review to identify the most common methods used by past investigators who placed pitfall traps for the purpose of quantifying indices of arthropod abundances, and used this information to guide our proposal for standardized pitfall trapping methods. We documented the pitfall-trap methods of 257 studies published between January 1994 and March 2016 in 107 scientific journals. Pitfall-trap methods varied greatly across the time period. We found only minor differences in the pitfall-trap methods most commonly used in different vegetation communities (e.g., preservative was used less frequently for pitfall trap studies in grasslands). Studies published in wildlife journals tended to use pitfall traps of larger diameters than studies published in other disciplines; these studies also had worse rates of methodological reporting than those in entomology journals. We did not detect a decline in negligent reporting over time; $\geq$1 key methodological detail was missing from >50% of studies regardless of the decade published. Published 2018. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS epigeic, ground-dwelling arthropods, insect sampling, pitfall traps, wildlife diet studies.

Arthropods are an important component of the diet for many species of wildlife, and wildlife researchers who work on insectivorous and omnivorous taxa often attempt to estimate relative abundance or species richness of arthropods for diet studies. Estimates of arthropod abundance are often used by wildlife researchers to test predictions from mechanistic hypotheses, compare the effectiveness of management treatments, and document diet selection by comparing foods eaten with foods available on the landscape. Pitfall traps are commonly used to estimate relative abundance of ground-dwelling arthropods and have been used in various ecosystems, from the arctic tundra to tropical rainforests (Norment 1987, Haugaasen et al. 2003). Indeed, pitfall traps are "probably the most commonly used method of catching invertebrates" (Bater 1996). Pitfall traps are popular because they are inexpensive and relatively simple to construct and deploy. The fundamental pitfall trap design is a container buried into the ground with the top flush with the soil surface. The simplicity of this method appeals to many wildlife researchers who wish to investigate patterns of arthropod abundance. For example, wildlife biologists may place pitfall traps to document or compare the availability of arthropod prey across different study sites. However, despite the apparent simplicity of pitfall traps, methods used to construct, place, and check pitfall traps vary widely among published studies and appear to reflect somewhat of an *ad hoc* approach to pitfall trap use. Brown and Matthews (2016) summarized 60 papers that used pitfall traps and documented some of the sources of that variation. Considerable variation in pitfall trapping methods makes comparisons among studies difficult and the lack of a standard method prior to Brown and Matthews (2016) has necessitated that investigators examine past studies when trying to determine his or her own trapping methods. But the subset of past studies examined likely varied considerably among investigators and, hence, led to the perpetuation of variation in pitfall trapping methods.

The need for a standardized pitfall trap has been acknowledged for 40 years (Adis 1979). Brown and Matthews (2016) conducted a literature review and proposed standardized methods for pitfall traps, but their review only included 60 papers, with only one from a wildlife journal. Moreover, their review focused on studies that used pitfall traps for documenting diversity, whereas ours focuses on studies that sought to quantify indices of abundance; the optimal pitfall trap methods likely vary depending on the

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objectives. Characteristics and sampling schemes of pitfall traps, which commonly vary among studies, include container size; container material and color; preservative or kill solution (if any) within the container; nested materials to reduce digging-in effects; the addition of drift fences, funnels, or trap covers; sampling intervals; and distance between adjacent traps (Brown and Matthews 2016). Most of these features have been shown to affect capture rates for beetles (Luff 1975, Waage 1985, Holopainen 1992, Radawiec and Aleksandrowicz 2013), ants (Greenslade 1973), spiders (Gurdebeke and Maelfait 2002, Schmidt et al. 2006), and other taxa (Obrist and Duelli 1996, Ward et al. 2001, Work et al. 2002, Schirmel et al. 2010, Skvarla et al. 2014). Rather than a reduction in methodological variation over time as might be expected in response to those publications, as well as the repeated recognition of the need for a more standardized method, variation has instead proliferated (Brown and Matthews 2016).

Standardized methods exist for many other sampling or trapping methods across a variety of taxa (Ralph et al. 1993, Powell and Proulx 2003, Ralph and Dunn 2004, Bloom et al. 2007, Bonar et al. 2009). Initial efforts to propose standard trapping or sampling methods are often controversial or outright rejected because scientists or resource managers prefer using familiar methods that they have used for years or those that they believe work well in their system or for the taxa they are targeting; these methods may or may not provide useful data (Peterson and Paukert 2009, Connelly et al. 2012; S. Droege, U.S. Geological Survey, personal communication). The development and acceptance of standard trapping methods are not intended to limit investigators' ability to use alternative methods better suited for their question or ecosystem. Rather, standard methods are useful for students, managers, or young professionals who seek a widely used and vetted method so their results are more readily comparable to other studies. We promote the need for a standard pitfall trapping method; therefore, to inform and support that goal, we conducted an extensive review of 921 papers that quantified invertebrate abundance. We sought to address 3 objectives: 1) document how commonly pitfall traps are used compared with other methods for sampling arthropods; 2) examine whether the most common methods varied among disciplines or major vegetation communities; 3) summarize the extent of variation in pitfall trapping methods used by past investigators; and 4) propose and promote standard pitfall trapping methods to help inform future investigators and produce more comparable data. As such, our paper builds upon Brown and Matthews (2016), who also addressed objectives 3 and 4 above. Our review was conducted prior to publication of Brown and Matthews (2016) and, although similar, our paper differs from (and improves upon) their paper in numerous ways: 1) our review of pitfall trap studies was part of a larger review of 921 studies that allowed us to quantify how commonly pitfall traps were used relative to other methods (objective 1 above); 2) our review was more thorough: they reviewed 60 studies that used pitfall traps, whereas we reviewed 257 studies (the other 664 papers used other methods or used pitfall traps for purposes other than abundance indices); 3) because of number 2 above, we provide much more thorough summaries of the percent of published studies that used different pitfall trap design features; 4) they reviewed only 1 study from a wildlife-related journal and 12 studies from ecology journals, whereas we reviewed 24 and 60 studies from those disciplines, respectively; 5) a third of the 60 studies they reviewed were published in entomology journals with other journal disciplines much less represented, while the 257 studies we reviewed were well-distributed among ecology, entomology, and multidisciplinary journals; 6) we examined whether the most common pitfall trap methods differed among disciplines or major vegetation communities (objective 2 above); and 7) we provide recommendations regarding the summary metrics that all future studies that use pitfall traps as indices of abundance report (to aid in future comparisons across studies or meta-analyses). We also summarized some aspects of pitfall trapping that they did not include in their summary (i.e., whether an initial latent period was included, whether drift fences were used, and spatial arrangement of traps). Moreover, the 257 pitfall trapping studies that we summarized only included 3 papers that were also included in the 60 listed in Brown and Matthews (2016). With this review, we also sought to draw more attention to the lack of clear methodological reporting across the majority of studies examined. With our extensive data set, we explicitly tested Brown and Matthews' (2016) assertion that pitfall trap reporting was declining over time. We call on authors to include, and reviewers and editors to demand (especially in wildlife journals), complete methodological details in all future studies that use pitfall traps (also see Brown and Matthews 2016).

METHODS

We conducted our literature review between November 2014 and March 2016. We used an online search engine (Academic Search Premiere) to identify peer-reviewed publications by researchers that had placed pitfall traps to catch arthropods. We used 'arthropod abundance' as our search criterion (rather than 'pitfall traps') because 1) we also wanted to document how often pitfall traps were used compared with alternative methods; and 2) we wanted to restrict our review to studies that used pitfall traps to generate estimates or indices of arthropod abundance, biomass, or frequency because pitfall methods used for these applications may differ from those used for other purposes (e.g., documenting community composition; Adis 1979). We examined only those articles published in English, and only studies published since 1994 because we suspected from the outset of our literature review that pitfall trapping methods may have changed over time (with the proliferation and advocacy of cheaper nontoxic alternatives for killing agents, for example). We excluded studies that used pitfall traps merely as means to capture a few voucher individuals (for laboratory rearing, chemical analyses, museum collections, etc.); we also excluded studies that used pitfall traps for mark–recapture population studies. We did not review articles if we did not have institutional access.

For each study that used pitfall traps and also met our criteria, we recorded the trap type (open-topped, funneled, or other), container materials and color, container dimensions, inter-trap distances, spatial arrangement of traps, presence or absence of sleeved–nested materials, presence or absence of trap covers, presence or absence of drift fences, if traps were placed before the start of the trap session, preservatives or kill solutions used (if any), sampling interval, and total deployment length. We noted if these details were unclear or not provided. If a trapping duration of $\leq$2 weeks was described without any mention of visits over the course of that time period, we assumed that no trap servicing had occurred and that this duration was equivalent to the sampling interval. Most of these same details were examined in the review conducted by Brown and Matthews (2016) as well. We kept a simple tally of all other methods of determining arthropod abundance we encountered and the number of methods used within each individual study.

We used analysis of variance (ANOVA) to test whether mean trap diameters or sampling intervals differed across land-cover types or among journal disciplines. We used *post hoc* Tukey's honest-significant-difference (HSD) tests to determine which land-cover types or journal disciplines differed following a significant ANOVA. We used unadjusted pairwise equality of proportion tests to examine whether funnel use, preservative use, and trap cover use differed across land-cover types or among journal disciplines. We also used unadjusted pairwise equality of proportion tests to examine whether different journal disciplines were prone to better or worse pitfall trap reporting. Incomplete reporting was determined by whether a manuscript included, at minimum, each of the following details: container material, container diameter, preservative specification, and sampling interval. Finally, we assessed whether overall pitfall trap reporting was in decline, as suggested by Brown and Matthews (2016). For this analysis, we grouped studies into 3-year intervals from 1995 to 2015. We used simple linear regression to investigate the relationship between publishing year and the percent of published studies that reported 6 details: container diameter, container height, container volume, container material, preservative, and sampling interval. All statistical analyses were conducted in R with $\alpha = 0.05$ for all statistical tests (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

The search term "arthropod abundance" returned 1,352 papers published between 1994 and March of 2016; 921 papers met our criteria and used their capture data to generate an index of arthropod abundance. Pitfall traps were used in 27.9% ($n = 257$) of the 921 studies. Other methods for estimating relative abundance were used less frequently: direct observations (21.6%), sweep-netting (12.0%), suction-sampling (11.1%), and soil core collection (10.7%; Fig. 1). More than one method was used in 23% of the 921 studies. The 257 studies that included pitfall traps in their methods were published in 106 different peer-reviewed journals. Most papers (55.6%) that used pitfall traps were missing at least

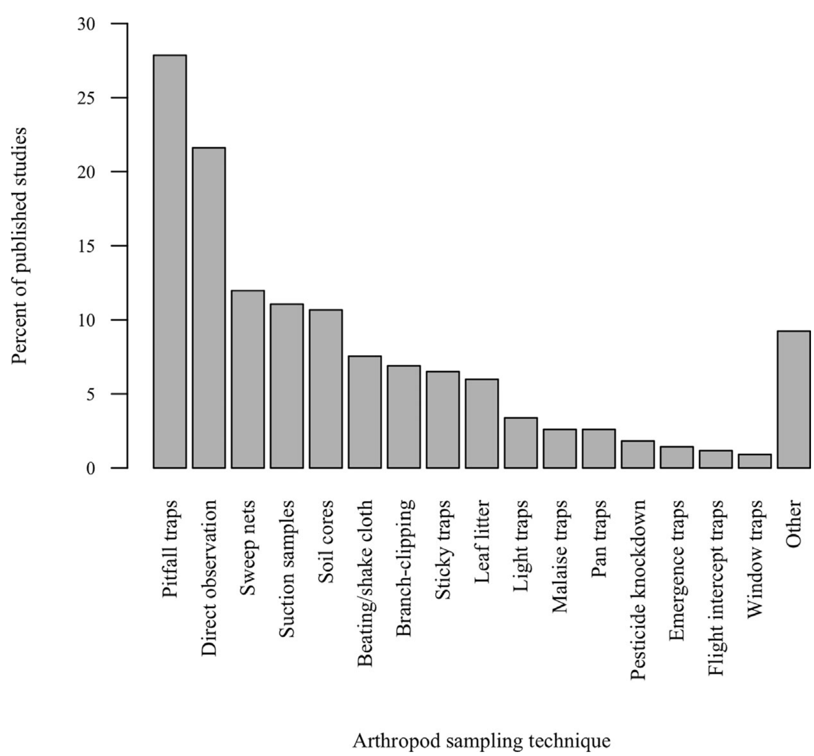

Figure 1. Percent of 921 journal articles published between January 1994 and March 2016 that used each of 16 common arthropod-sampling techniques within studies that sought to measure an index of arthropod abundance or biomass. The cumulative percentage (across all sampling methods) is >100% because many studies used more than one technique to generate indices of arthropod abundance.

one of the following pieces of information: container material, container diameter, preservative specification, or sampling interval.

Published papers that had used pitfall traps were more numerous during the second half of the time period investigated (i.e., use of pitfall traps has increased over time). Fifty-three papers that met our criteria were published between 1994 and 2004, whereas the remaining 204 were published between 2005 and March of 2016 (Fig. 2).

Few papers we reviewed used pitfall traps that targeted any specific taxa, but were rather investigating trends for “all arthropods,” “all ground-dwelling arthropods,” or all “litter arthropods,” etc. (71.5%, $n = 186$). For those trapping for specific taxa, Coleoptera ($n = 42$) and Araneae ($n = 35$) were the 2 most targeted orders, though rarely were either of these mentioned as the only taxon of interest. These 2 taxa were more often studied simultaneously or along with other focal taxa.

Trap Type

Twenty-nine papers explicitly stated use of funnels (11.3%). Five studies drilled holes either into the lid itself or around the circumference of the container, with containers protruding above the soil surface and arthropods entered through the drilled holes (e.g., Nordlander 1987). The remainder (86.8%) did not mention funnels or lids, and we assumed these were the basic open-topped pitfall trap design. No studies used ramped pitfall traps.

Container Specifications

Container materials and colors.—Most studies that placed pitfall traps used plastic containers (60.7%, $n = 156$), the majority of which were plastic drinking cups ($n = 100$). Other researchers used plastic pitfall traps consisting of bottles, buckets or pails, plastic test tubes or vials, beakers, pots, and jars. Only 17 studies (10.9%) that used plastic containers reported the color of their traps (9 transparent, 5 white, 3 yellow). Seven studies (2.7%) used traps made of glass, including test tubes or vials and jars. Three studies used metal traps (consisting of tin, aluminum, or steel cans). Ninety-one studies (35.4%) did not report the material of their pitfall trap containers.

Container dimensions.—For the 217 studies that used the common open-topped pitfall trap type (excluding traps with funnels or with nested materials of differing dimensions), investigators used containers with diameters ranging from 0.25 cm to 50 cm ($\bar{x} = 8.8$ cm; mode = 10 cm), heights ranging from 5.2 cm to 65 cm ($\bar{x} = 12.0$ cm; mode = 10 cm), and volumes ranging from 0.035 L to 100 L ($\bar{x} = 3.0$ l; mode = 0.50 L). Overall, investigators were more likely to report the diameter ($n = 197$) than the height ($n = 123$) or volume ($n = 86$) of the pitfall trap container they used.

Preservatives and Kill Solutions

Twenty-seven studies (10.5%) lacked information regarding whether preservatives or kill solutions were used in their pitfall traps. Of those that did explicitly state whether solutions were used, 91.3% ($n = 210$) used some form of preservative or kill solution within the pitfall traps (Fig. 3). Only 7.8% used dry traps ($n = 20$). One study that used dry traps placed insecticide cattle ear tags within their pitfall traps to kill the captured insects, whereas 2 other studies lined the bottom of the pitfall traps with Tangle-trap.

Ethylene glycol was the most common preservative; 29% of the 210 studies that used a preservative used ethylene glycol (either pure or dilute). Eight of the 61 studies that used ethylene glycol added a small amount of detergent to the solution to decrease the surface tension. Twenty-two percent of the 210 studies used water in the traps (5 used pure water, 6 used salt water, 18 used water with a drop of detergent, 10 used soap water, and 8 used salt water with a drop of detergent). Fifteen percent of the 210 studies used propylene glycol (either pure or dilute). Four of these studies added a small amount of detergent to decrease the surface tension. One study also added a small amount of formaldehyde (0.1% of the total solution), and another added propylene phenoxetol (a biodegradable, nontoxic antibacterial agent).

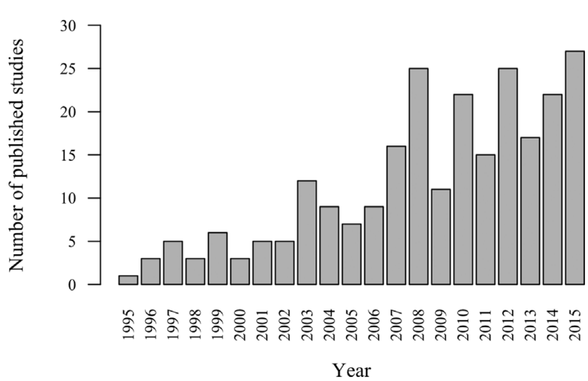

Figure 2. We conducted a literature review by using the search phrase “arthropod abundance” and reviewed 921 papers; studies that placed pitfall traps to investigate arthropod abundance were increasingly common between 1995 and 2015.

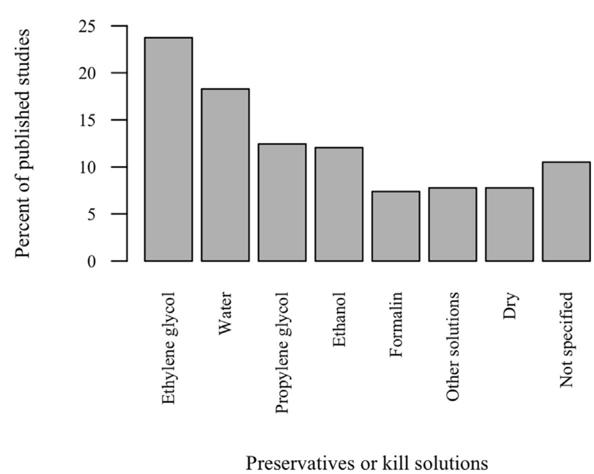

Figure 3. Percent of published studies that used (or did not use) various preservatives or kill solutions in pitfall traps based on 257 studies published January 1994–March 2016 that employed pitfall traps for the purpose of measuring an index of arthropod abundance. “Not specified” refers to studies that did not report whether a preservative was used or not.

Fifteen percent of the 210 studies used ethanol. Seven of these studies also added a drop of detergent, 2 added glycerol, and another added a small amount of mineral oil to decrease evaporation. Nine percent of the 210 studies used dilute formaldehyde (solutions ranged from 1% to 10%, but most used 3–4%). Six studies that used formaldehyde as the primary preservative also added a drop of detergent to the solution. Two used formaldehyde in a saturated salt solution, and another added glycerol to the dilute formalin. Nine percent of the 210 studies used a cocktail of kill solutions or some less common solutions, including 4 that used wine vinegar and 3 that used a general attractant and kill solution known as "Turquin's solution" consisting of dark beer, preservatives, and a few drops of detergent (Turquin 1973).

Other Modifications to Trap Design

Nested or sleeved containers.—Fifty-one (19.8%) of the 257 studies used sleeved ($n = 25$ studies) or nested ($n = 26$ studies) pitfall traps. Nested and sleeved pitfalls protect the actual trap from crushing and also hold the surrounding terrain in place so traps can more easily be serviced or emptied and redeployed. Sleeves are bottomless cylinders inserted into the ground that hold the primary pitfall receptacle in place. Sleeves often were made of polyvinyl chloride piping. Nested pitfalls were either 2 of the same containers inserted together ($n = 6$) or a larger, second container within which the first was nested ($n = 20$). Five of the 20 studies that used a second, larger container drilled holes in these secondary containers to allow the escape of rainwater and avoid flooding. However, most studies (80.2%, $n = 206$) did not use (or did not mention the use of) nested or sleeved traps.

Trap covers.—Covers (or rain guards) are elevated above the ground (and above the lip of the pitfall trap) and still allow arthropods to pass underneath the cover and fall into the open trap (versus lids, mentioned above under "Trap Type," which were placed directly onto the pitfall trap itself). Researchers place covers above their pitfall traps for one or more of the following reasons: to prevent rain from filling the traps, prevent leaf litter and other organic material from falling into the traps, slow evaporation of the preservative, prevent large vertebrates from trampling the traps, prevent small vertebrates from inadvertently falling into the trap, or prevent vertebrates from attempting to eat the captured arthropods. Eighty of the 257 studies (31.1%) placed trap covers above their pitfall traps. Most of these researchers placed trap covers between 2 and 5 cm above the top of the pitfall trap. Fifty percent of the studies that placed covers over traps did not report the height at which covers were placed. Trap cover materials were variable: 41 studies used plastic covers, 14 used wood covers, 6 used metal covers, 6 used ceramic or tile covers, 2 used Styrofoam covers, 2 used Plexiglas covers, and 14 did not specify what type of cover they used. The remaining 177 studies did not place trap covers above their traps (or did not mention doing so). Nine (3.5%) of the 257 studies used wire or steel mesh over the mouth of the trap (instead of a trap cover to prevent vertebrate by-catch, protect the traps from depredation, or both).

Drift fences.—Fourteen studies (5.4%) placed drift fences or barriers beside pitfall traps or between arrays of traps. Drift fences are used to increase capture efficiency of pitfall traps. Five studies used galvanized or aluminum sheet metal, 2 used Plexiglas®, 1 used plastic mesh, 1 used fiberglass, 1 used a clear plastic material, and 4 reported using drift fences but did not report the drift fence material. The length of the drift fence affects capture probability (and hence the ability to compare results among studies; Brennan et al. 2005, Skvarla et al. 2014), but only 9 of the 14 studies that used drift fences reported the length of the drift fences they used. Cumulative drift-fence lengths (one pitfall trap often had 2 or 4 drift fences radiating from the trap) ranged from 1.1 m to 5 m when traps were placed individually. Cumulative drift fence lengths associated with arrays of interconnected traps ranged from 1.6 m to 18 m.

Inter-trap Distance and Spatial Arrangement

Less than half of the 257 studies reported the distance between adjacent pitfall traps ($n = 123$, 47.9%). Reported distances between adjacent pitfall traps ranged from 0.15 m to 100 m. The 3 most common inter-trap distances were 10 m ($n = 30$), 5 m ($n = 25$), and 2 m ($n = 11$). Fifty-two studies reported their pitfall trap arrangements as transects, 31 reported grids or rectangles, 7 reported setting traps in pairs, 3 reported trap arrangements as triangles, 2 reported circular trap arrangements, and 6 reported arrangements as arrays or clusters of multiple pitfall traps that were connected by drift fences or barriers.

Early Trap Placement

Ten studies (3.9%) explicitly mentioned positioning their traps and closing them with lids before the sampling period and then waiting some time before opening the traps. This approach (to include a latent period between trap placement and the start of the initial trapping session) is intended to reduce any potential effects of the disturbance associated with trap placement on capture efficiency. Early trap placement ranged from 1 day to 1 month before sampling began, but 5 days was the most common length of the latent period.

Sampling Interval

Most studies reported the frequency or interval between when traps were emptied ($n = 240$, 93.4%). Intervals between trap checks ranged from 12 hr to 38 days ($\bar{x} = 8.0$ days). The most common interval was 7 days ($n = 59$) between trap checks, and the other most common intervals were 1 day ($n = 36$), 2 days ($n = 26$), 3 days ($n = 24$), 5 days ($n = 18$), 10 days ($n = 15$), 2 weeks ($n = 28$), and 1 month ($n = 10$; Fig. 4). Decisions regarding trap check intervals were influenced by the number of desired samples, volume of the traps, catch rate, amount and type of preservative used, and other logistical issues. For example, propylene glycol and ethylene glycol have slower evaporation rates relative to water or ethanol and allow investigators to leave traps deployed longer.

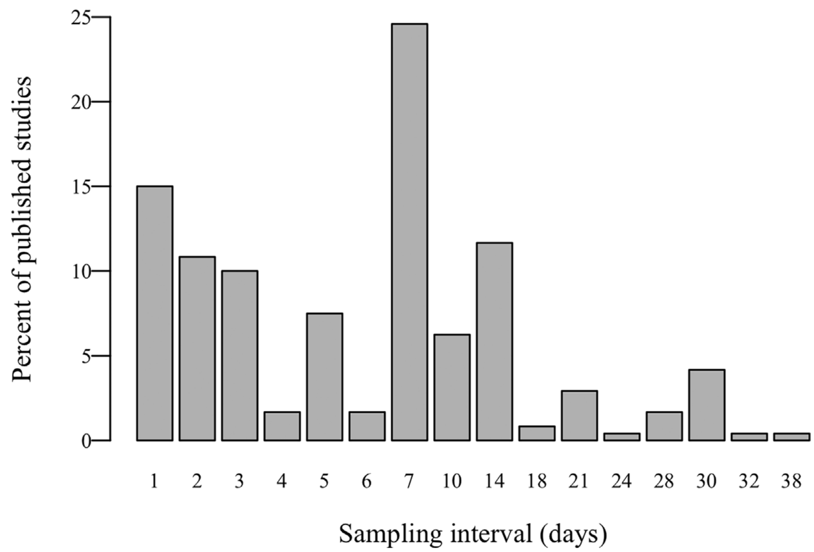

Figure 4. Intervals between when pitfall traps were checked varied greatly (range = 1–38 days, median = 7 days) among 240 studies that placed pitfalls for the purpose of measuring an index of arthropod abundance. Seventeen of the 257 studies published between January 1994 and March 2016 that we reviewed failed to report the sampling interval.

Differences in Pitfall Trapping Methods among Vegetation Communities and Land Use Types

The most effective or common pitfall trapping methods may vary among vegetation communities, so we summarized past studies separately for each of the 4 most commonly encountered vegetation communities or land uses: agricultural land (including cropland, fields), forest (including tree plantations, boreal forests, rainforests), shrubland (including scrubland, sage brush, heathlands, shrub–grass steppe, fynbos), and grassland (including steppes, savannas, meadows, and pasture). The most common trapping methods did not vary greatly among the 4 categories, with only a few exceptions (Table 1). Studies that occurred in grasslands had the most disparate pitfall trap characteristics and methods. These studies were more likely to check traps every 14 days rather than every 7 days, though the overall mean sampling intervals for pitfall traps used in each category did not differ ($F_{3,188} = 2.13$, $P = 0.098$). Pairwise equality of proportions tests concluded that a smaller percentage of studies placed pitfall traps containing preservatives or kill solutions in grasslands compared with studies in agriculture ($\chi^2_1 = 7.46$, $P = 0.006$) or forest land covers ($\chi^2_1 = 7.75$, $P = 0.005$). Studies in grasslands were equally likely to have used ethanol as ethylene glycol solutions. Studies that placed pitfall traps in agricultural systems used water as a preservative or kill solution more frequently than ethylene glycol.

Differences in Pitfall Trapping Methods among Disciplines

The reviewed manuscripts were published in journals representing 7 broadly defined disciplines: entomology, ecology, wildlife, agriculture–pest management, forestry–soils–zoology, biogeography–conservation biology, and multidisciplinary–other (Table 2). Funnel and trap cover use did not differ among any of these disciplines ($\chi^2_6 = 6.75$, $P = 0.34$, and $\chi^2_6 = 3.77$, $P = 0.71$, respectively). Preservative use also did not differ among disciplines ($\chi^2_6 = 11.01$,

Table 1. Pitfall trap methods used in studies published between January 1994 and March 2016 for each of 4 broadly defined vegetation communities and land use types.

	Vegetation type				
Pitfall trap specifications	**Agriculture**	**Forest**	**Shrubland**	**Grassland**	**Overall**[d]
Funnel traps (%)	14.5	10.5	13.6	10.9	11.3
Mean trap diameter (cm)	9.6	8.9	8.3	10.6	8.8
Traps with solutions (%)	90.3A[a]	89.5A	90.9AB	67.4B	91.3
Most common solution	Water	E. glycol[b]	E. glycol	Ethanol, E. glycol[c]	E. glycol
Traps with covers (%)	41.9	35.5	27.3	26.1	31.1
Mean sampling interval (days)	7.4	9.3	5.7	10.1	8.0
Most common sampling interval (days)	7	7	7	14	7
Total studies	62	76	22	46	257

[a] Values that share letters do not differ among vegetation types ($P > 0.05$).
[b] Ethylene glycol.
[c] Ethylene glycol and ethanol were tied as the most common solution.
[d] Metrics from across all studies with pitfall traps published within the time period (51 of the 257 studies were not located in either of the 4 vegetation types, or did not state the vegetation type).

Table 2. Pitfall trap methods reported in 257 manuscripts in 106 different journals from 7 broadly defined disciplines published between January 1994 and March 2016.

	Journal discipline						
Pitfall trap specifications	**Entomology**	**Ecology**	**Wildlife**	**Agriculture–pest management**	**Forestry–soils–zoology**	**Biogeography–conservation biology**	**Multidisciplinary–other**
Funnels (%)	17.0	5.0	12.5	16.7	14.3	16.0	6.1
$\bar{x}$ trap diameter (cm)	10.3AB[a]	7.7A	11.6B	9.3A	8.2A	8.1A	8.8A
Traps with solutions (%)	87.0	96.0	95.2	95.2	100.0	91.7	81.4
Traps with covers (%)	38.3	28.3	20.8	41.7	35.7	32.0	34.7
$\bar{x}$ sampling interval (days)	7.4	7.7	5.2	10.5	10.2	8.8	7.7
Missing information[b] (%)	38.3A	60.0B	66.7B	54.2AB	35.7AB	60.0AB	51.0AB
Total studies	47	60	24	24	28	25	49

[a] Values that share letters do not differ among journal disciplines ($P > 0.05$).
[b] Percent of manuscripts missing $\geq$1 of the following pieces of information: container material, diameter of trap, preservative description, or sampling interval.

$P = 0.09$). Mean sampling intervals were comparable across all disciplines ($F_{6,233} = 1.40$, $P = 0.21$). Diameter of pitfall traps differed among journal disciplines ($F_{6,190} = 4.22$, $P \leq 0.001$). The *post hoc* Tukey's HSD test revealed that pitfall trap diameters were larger in wildlife journals than they were in ecology, agriculture–pest management, forestry–soils–zoology, biogeography–conservation biology, and multidisciplinary–other journals. Pitfall trap reporting was more complete for manuscripts published in entomological journals than it was for either ecology ($\chi^2_1 = 4.14$, $P = 0.04$) or wildlife journals ($\chi^2_1 = 4.05$, $P = 0.04$).

Pitfall Trap Reporting Over Time

We found an improvement in the reporting of container diameters (4.8% improvement every 3 yr; $F_{1,5} = 23$, $P = 0.005$, $r^2 = 0.79$) and container volumes (2.1% improvement every 3 yr; $F_{1,5} = 6.83$, $P = 0.05$, $r^2 = 0.49$) over time (Fig. 5). The only detail for which we found decreasing rates of reporting was container material, though this relationship was not significant ($F_{1,5} = 0.80$, $P = 0.41$, $r^2 = -0.04$).

DISCUSSION

Past investigators have used pitfall traps more than any other technique to measure arthropod abundance or biomass and the use of pitfall traps has increased over time. However, pitfall trapping methods used by past authors varied tremendously among the 257 papers published between 1994 and 2016 that we reviewed. Our results corroborate many of the results reported by Brown and Matthews (2016) with the following exceptions: we report greater rates of funnel traps (11% vs. 3%); greater proportions of studies that used ethylene glycol solutions (29% vs. 18%); and they did not mention the use of water as the trap solution (which was the second most commonly used pitfall trap solution in our

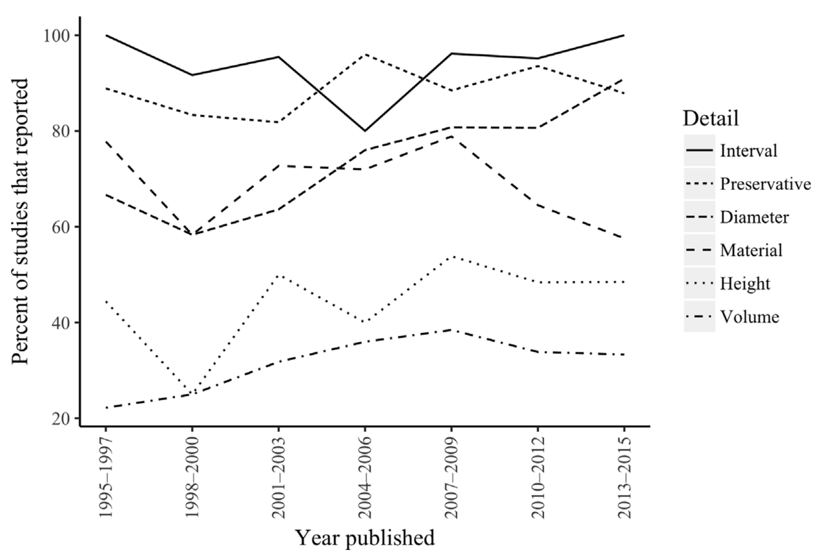

Figure 5. Lack of evidence for increasing negligence in methodological reporting of pitfall trap efforts in 248 studies published between 1995 and 2015. The only detected trends over time during this 20-year interval were increasing rates of reporting container diameters and container volumes ($P < 0.05$).

review). Our review was much more thorough (257 vs. 60 papers) and included many more papers in the fields of ecology and wildlife science. As such, our paper provides a summary and bibliography for future ecologists and wildlife scientists who wish to use pitfall traps to estimate arthropod abundance.

The large variation in pitfall trap methodologies used in past studies limits the ability to compare results across studies and hinders future comparative analyses, but may reflect investigators' efforts to use pitfall traps best suited for their question or study system. However, much could be gained if future investigators conformed to some standard methods, where doing so does not sacrifice study objectives. For example, many researchers did not take advantage of simple modifications that could make their pitfall traps more efficient. Nested containers have a negligible cost and greatly increase the ease with which traps are placed and serviced, but only one-fifth of researchers nested their pitfall traps. Trap covers have numerous benefits including reducing the risk of pitfall traps being rained out or accumulating debris, helping to protect the traps from depredation or trampling by vertebrates, and slowing the evaporation rate of the preservative. Yet only one-third of past pitfall trap studies covered their traps. Furthermore, most researchers did not appear to have taken measures to limit by-catch. Ethylene glycol was the most commonly used preservative despite its known toxicity and a readily available nontoxic alternative (propylene glycol) that is only slightly more expensive and has comparable capture and preservation rates (Hall 1991, Weeks and McIntyre 1997). Funneled pitfall traps were uncommon despite their demonstrated ability to decrease vertebrate by-catch and potentially increase retention of captured invertebrates (Pearce et al. 2005, Lange et al. 2010, Brown and Matthews 2016).

The standardization of pitfall trapping methods would greatly improve the ability to compare one's results with other studies and make it much easier to pool data across studies for comparative studies and meta-analyses. These benefits are especially useful for studies that seek to quantify arthropod abundance metrics. Brown and Matthews (2016) recently proposed a standardized pitfall trap design, which, if embraced by the wildlife community, would help future researchers to produce data that would allow more synthetic analyses. Based on our thorough review of the literature, we suggest some additional details to further standardize future pitfall trapping efforts (Table 3). Inter-trap spacing has a demonstrable effect on estimates of species richness (Digweed et al. 1995, Ward et al. 2001); hence, we propose a standardized trap spacing of 10 m. This was the most common inter-trap distance reported across the studies we reviewed, and 10 m was also the largest of the 3 most commonly reported inter-trap distances. We also suggest that researchers service and empty their pitfall traps every 7 days so that produced data are more comparable across studies. This was the most common sampling interval reported in the papers we reviewed and yields greater capture rates of arthropods compared with longer sampling intervals (Schirmel et al. 2010). More frequent visits to the traps could have unwanted effects as a result of increased levels of disturbance to the study site (Schirmel et al. 2010). However, researchers that opt for preservatives with greater evaporation rates (like ethanol) will likely need to visit traps more frequently. The optimal preservative depends upon the goals of the study (e.g., ethanol is better for DNA preservation, Gurdebeke and Maelfait 2002). Skvarla et al. (2014) recently provided a review of different pitfall trap preservatives.

Table 3. Recommended methodology to standardize use of pitfall traps for obtaining indices of arthropod abundance. We have expanded upon Brown and Matthews' (2016) suggested standardized trap methods with additions and modifications based on our literature review of 257 studies that used pitfall traps.

Trap container	Transparent plastic cups[a], nested (2-cup design)[a]
Diameter	9–11 cm[a]
Funnel	Transparent[a]
Preservative	Propylene glycol, or other nontoxic solution[a]
Cover	Transparent[a], 2–5 cm above ground
Sampling interval	7 days (or less)
Trap placement	Transect, 10 m apart

[a] Specifications suggested by Brown and Matthews (2016).

Our review, as well as that of Brown and Matthews (2016), included many studies that were doing broad analyses of the entire epigeic community rather than targeting specific orders. Only 26 of the 257 pitfall trap studies we reviewed targeted either Araneae or Coleoptera in isolation and studies that targeted other Orders were even less common. Researchers seeking to study only 1 or 2 specific arthropod orders would benefit from seeking out studies that have compared capture rates of various designs for those taxa. The inclusion of funnels and trap covers will affect the capture of flying arthropods as they reduce the surface area exposed aerially (Kuschka et al. 1987 cited in Obrist and Duelli 1996). However, flying arthropods are not particularly well-sampled by pitfall traps, and many more appropriate methods for sampling flying arthropods are available (e.g., sticky traps, sweep netting, malaise traps; Juillet 1963, Norment 1987, Zou et al. 2012). Researchers interested in both the epigeic and flying arthropod communities should consider using complementary sampling methods (e.g., pitfall traps and malaise traps).

Even if researchers are unable to use the proposed standardized design, pitfall trap data gathered in future studies would be more beneficial if investigators reported all of the pitfall trap methods used, including details of the aforementioned characteristics of pitfall traps and placement and servicing techniques. Similar to Brown and Matthews (2016), our review documented a negligence in methodological reporting in past pitfall trapping studies. However, unlike Brown and Matthews (2016), we did not find evidence for a decline in methodological reporting over the time period we investigated. In fact, pitfall trap reporting may be slowly improving, though standards are still not up to what should be expected from the scientific community. Less than half of the studies we examined contained sufficient methodological detail. For example, 10% of published studies that used pitfall traps failed to mention if their traps even contained preservatives or kill solutions, which can greatly affect the frequency with which certain groups of arthropods are captured (Adis 1979, Weeks and McIntyre 1997, Skvarla et al. 2014). The color of the pitfall trap influences capture rates of several taxa of arthropods, but 87.4% of studies that used plastic pitfall traps failed to report the color(s) of the containers they used (Buchholz et al. 2010). Details about the total trap effort (total duration of trap effort in combination with sampling intervals) were often confusing because many authors included only statements about one or the other without specifying to which they were referring. For example, if an author merely stated that "pitfall traps were open for one month," are we to assume they had visited and emptied the traps only once (at the end of the month)? Hence, future publications should address both the total duration of trap effort and explicitly state how often traps were emptied or serviced during this time. Terms such as "bimonthly" or "biweekly" should be avoided, as their meaning is open to interpretation.

Pitfall trapping is used for a variety of purposes. Many studies have used pitfall traps to quantify relative estimates of abundance or biomass (typically counts standardized by unit of effort) rather than absolute estimates of abundance or biomass (Pedigo and Buntin 1993). In such studies, detailed descriptions of the methods used and results obtained are essential for comparisons, especially those related to trap effort, such as the number of traps set, the interval between when traps are emptied (if traps are left in place over multiple capture events), the duration of the trapping effort, and the diameter of the trap opening. Any additional modifications to trap design that affect effective trap effort (such as including drift fences) should be well-documented.

In addition to variation in methods used to deploy pitfall traps, studies also varied in the metrics used to summarize the arthropods captured in their pitfall traps. Hence, we suggest all future studies that use pitfall traps to quantify abundance or biomass report the following metrics: raw abundance (total no. of individuals captured), raw biomass, average number of individuals captured per pitfall trap per day, average biomass (dry weight per pitfall trap per day), and all of the metrics above by taxonomic level (total, as well as by Order, Family, Genus, Species, whenever possible). Studies should also consider reporting the above metrics by size classes. Identifying arthropods to Order is not too difficult and should be feasible for all studies (as a minimum). If all studies report results by Order (in addition to lower levels of taxonomic scale as funding, interest, and expertise allow), results will be more easily compared across studies.

Investigators should use the pitfall trapping methods best suited for their question or study location. When no obvious method is best, investigators would benefit from using 1) one or more of the design features proposed here (also see Brown and Matthews 2016), or 2) methods used by other studies in the same ecosystem or those that targeted the same taxa (Table S1, available online at www.onlinelibrary.wiley.com). In some situations, investigators will have to weigh whether to use a method commonly used by other studies or one less commonly used but might be more appropriate for their study.

Investigators using pitfall traps should interpret their catch data with the appropriate caveats. The bias of this technique toward certain taxa has been well-documented (e.g., more active terrestrial taxa will be caught disproportionately, preservatives differentially attract some taxa, some species exhibit more successful escape behaviors, etc. (Mitchell 1963, Greenslade 1964, Henderson and Southwood 2016). Because of these well-known biases, data from pitfall traps are usually not appropriate to compare relative abundance among different taxa (Topping and Sunderland 1992, Skvarla et al. 2014). Furthermore, activity levels of arthropods affect their capture rates in pitfall traps and activity levels even within species are known to vary depending upon weather, time of day, and season (Topping and Sunderland 1992, Melbourne 1999). Additionally, the structure of the vegetation in the immediate surroundings of the pitfall traps also has an influence on capture rate (Melbourne 1999). These caveats associated with pitfall traps have been known (in some cases) for decades, but yet there has been a preponderance of misconceptions about the applicability of pitfall trap data toward answering certain ecological questions (Topping and Sunderland 1992). Despite the caveats above, pitfall traps do present an inexpensive and effective (and potentially standardized) tool for providing relative abundance estimates of arthropods across space and time if investigators consider, and make efforts to avoid, extraneous sources of variation (Topping and Sunderland 1992, Skvarla et al. 2014, Henderson and Southwood 2016).

All trapping methods have inherent biases. Results obtained from pitfall traps are likely to be less biased and allow greater inferences if future studies 1) use standardized pitfall trapping methods; 2) include explicit, detailed descriptions of the methods used; and 3) include summaries of capture results that are common across studies. We believe that the summary included in this paper and recommendations provided regarding a standardized pitfall trap methodology gives future investigators who wish to use pitfall traps to estimate or compare arthropod abundance or biomass a useful 'starting point' and allows them to more quickly identify the most suitable (and most comparable) pitfall sampling methods.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site. This includes the complete list of reviewed articles that used pitfall traps to investigate arthropod abundance and the associated pitfall trap methods.