Pauli, N., L. K. Abbott, S. Negrete-Yankelevich, and P. Andrés. 2016. Farmers' knowledge and use of soil fauna in agriculture: a worldwide review. *Ecology and Society* 21(3):19. http://dx.doi.org/10.5751/ES-08597-210319

Synthesis

Farmers' knowledge and use of soil fauna in agriculture: a worldwide review

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ABSTRACT. General knowledge of the small, invisible, or hidden organisms that make soil one of the most biodiverse habitats on Earth is thought to be scarce, despite their importance in food systems and agricultural production. We provide the first worldwide review of high-quality research that reports on farmers' knowledge of soil organisms in agriculture. The depth of farmers' knowledge varied; some farming communities held detailed local taxonomies and observations of soil biota, or used soil biological activity as indicators of soil fertility, while others were largely unaware of soil fauna. Elicitation of soil biota knowledge was often incidental to the main research goal in many of the reviewed studies. Farmers are rarely deliberately or deeply consulted by researchers on their existing knowledge of soil biota, soil ecology, or soil ecological processes. Deeper understanding of how farmers use and value soil life can lead to more effective development of collaborative extension programs, policies, and management initiatives directed at maintaining healthy, living soils.

Key Words: *agriculture; ethnoecology; ethnopedology; farmer knowledge; local knowledge; soil biota*

INTRODUCTION

The sustainability of our food systems depends on the maintenance of healthy soils. In recognition of the crucial importance of soils, 2015 was proclaimed by the United Nations as the International Year of Soils. The organisms that inhabit soils are responsible for many ecosystem services (Bardgett and van der Putten 2014). The soil system is likely to harbor the greatest concentration of terrestrial biodiversity, although the vast majority of species are undescribed (Decaëns 2010, Jeffery et al. 2010). Worldwide, there are thought to be 900,000 species of mites, 200,000 species of soil-dwelling protozoa, and upward of 1,000,000 species of soil-dwelling fungi, compared with an estimated 300,000 species of vascular plants (Barrios 2007). The soil habitat is complex and opaque, which presents substantial challenges to scientists and farmers interested in understanding soil ecology and biology.

Arguably, until recently soil biology has lived a niche existence (Wall et al. 2010), with little influence on policy and limited appreciation among the wider public of the value and diversity of soil biota (Breure et al. 2012). Soil biodiversity is seldom addressed in national policy (GSBI 2012), and the UN Convention on Biological Diversity (1992) only adopted a cross-cutting theme on soil biodiversity in 2006 (CBD COP 8 Decision VIII/23). The European Union's withdrawn proposed Soil Framework Directive stated that although soil biodiversity loss was one of the eight major degrading processes affecting European soils, scientific knowledge was "too limited to allow for specific provisions...aiming at its protection" (Commission of the European Communities 2006:10). There are suggestions of growing awareness in policy circles of the importance of soil organisms in attaining broader goals in agriculture, food security, and global change (Wall et al. 2010, Bardgett and van der Putten 2014), but few studies have provided specific recommendations on how to incorporate soil organisms and soil biological processes into management, planning, and policy frameworks.

Although most policy makers may rarely give a thought to soil life, there is one diverse group of people who might well value and hold detailed knowledge about soil organisms: farmers who make their living from the land. We propose that greater understanding of how farmers view soil life can help in the development of extension programs, policies, and management initiatives directed at maintaining healthy soils. The literature reporting on how farmers value and understand soil organisms in an agricultural context has not yet been systematically examined at a worldwide scale. This literature is diffuse and dispersed, belonging to several disciplines that rarely intersect. Two published reviews discuss local knowledge on soil biology for the African region for termites (Sileshi et al. 2009) and pests and pathogens (Sekamatte and Okwakol 2007). Related topics where reviews have proven insightful include: entomophagy (insect-eating; Gahukar 2011); environmental manipulation for insect procurement (Van Itterbeeck and Van Huis 2012); traditional pest management (Morales 2002); entomotherapy (medicinal uses of insects; Costa-Neto 2005); and local ecological knowledge of fungi (de Roman 2010), insects (Posey 1986), and soils (ethnopedology; Barrera-Bassols and Zinck 2003, WinklerPrins and Barrera-Bassols 2004). Much has been written and reviewed on local knowledge of soil physical and chemical properties as well as soil, land, and water management (see Barrera-Bassols and Zinck 2000), but soil biological knowledge is far less widely reported.

We present a worldwide synthesis of peer-reviewed journal articles and high-quality grey literature research on local farmer knowledge of soil biota in agriculture, encompassing a wide range of agricultural systems and cultural contexts. We note that what has been published in the available literature presents only a small fraction of what is actually known by farmers. Our review is limited to visible fauna; although our original intention was to include all soil organisms, we found few papers that addressed farmer knowledge of fungi, rhizobia, or soil microbes in an agricultural context (Romig et al. 1995, Sillitoe 1995, Grossman 2003, Lobry de Bruyn and Abbey 2003, Kelly et al. 2009,

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Miyagawa et al. 2011), and these papers also discussed visible soil fauna. The aims of the review are the following: (1) to identify patterns in geographic regions, farming systems, and groups of organisms represented in the studies; (2) to ascertain the common themes addressed, and the primary research motivations; (3) to apply a conceptual framework used in ethnoecology to explore how farmers perceive, value, and use soil biota; and (4) to set an agenda to guide future work in extension, management, policy, and research.

Local, hybrid, and scientific ecological knowledge

Scientific research is not the only means by which people develop a meaningful understanding of their surroundings. Local, traditional, indigenous, experiential, and tacit are terms commonly used to describe knowledge systems drawn from sources other than the formal scientific method. Hybrid knowledge can be viewed as the fusion of local knowledge and new expert or technical knowledge gained from external sources, such as agronomists or scientists (Barrios et al. 2006, Reid et al. 2011), although Raymond et al. (2010) caution against overly simplistic categorization of environmental knowledge along a spectrum from local to hybrid to scientific. By combining local experience with global perspectives, the integration of different forms of knowledge can lead to insights into sustainable management, and reduce the risks associated with sustaining livelihoods in marginal environments, or during periods of rapid environmental change (Oberthür et al. 2004, Reed et al. 2007). From a resilience perspective, where local knowledge is seen as influencing the adaptability of social-ecological systems, integration of diverse sources of knowledge is thought to aid management of complexity and uncertainty (Folke et al. 2005), although empirical evidence remains scarce (Bohensky and Maru 2011).

Given the subtleties around what constitutes local ecological knowledge, we have adopted a broad definition that allows our analysis to encompass a wide range of different knowledges, geographic regions, agroecosystems, and socioeconomic contexts. Here, "local knowledge" comprises knowledge gained by indigenous people, farmers, and other resource users based on interactions with their environment, society, and culture over time. Similarly, a broad definition of "farmer" is used to encompass any person practicing cultivation of annual or perennial crops and/or rearing of livestock, for subsistence, exchange, or sale outside the household.

The process by which people incorporate observations on biological interactions and ecological processes into natural resource management and their worldview is known as the *corpus-praxis-kosmos* complex (or "knowledge-practice-belief") in ethnoecology (Berkes et al. 2000, Barrera-Bassols and Toledo 2005). The *corpus* or body includes people's observations on climate, soils, plants, animals, and vegetation, which may be gained individually or collectively over generations. *Praxis* encompasses activities that use the body of environmental knowledge to harness resources, and includes agriculture, horticulture, hunting, fishing, beekeeping, agroforestry, livestock, and resource extraction. *Kosmos* includes culturally important concepts and constructs such as sacred spaces, rituals, myths, and elements of the belief system and moral code. The three domains overlap, and at their centre lies the "Ethnoscape," which views a landscape as a socio-cultural construct rather than a purely biophysical one (Barrera-Bassols and Toledo 2005). We use this conceptual framework, with its explicit recognition that local environmental knowledge reaches beyond simply identifying or labeling particular features, to review the contributions and research gaps of studies on farmer knowledge of soil fauna in agriculture.

METHODS

The body of case studies in this review were published in peer-reviewed journals and in high-quality grey literature to December 2015. Systematic keyword searches of online journal databases using combinations and contractions of relevant terms including "knowledge," "farmer," "local," "traditional," "indigenous," "ecological," "agriculture," "soil," "fauna," "biota," "biology," and "organisms" were conducted periodically to add new case studies, as well as cross-referencing citations of and within qualifying articles. High quality grey literature (including PhD and MSc theses) was sought via searches of the following: (i) the ProQuest Dissertations and Theses Database; (ii) online publication databases of relevant, renowned sources, Centro Internacional de Agricultura Tropical (CIAT), the Food and Agriculture Organization of the United Nations (FAO), and the World Agroforestry Centre (ICRAF); and (iii) a subject-indexed annotated bibliography of ethnopedological studies (Barrera-Bassols and Zinck 2000). The search was conducted in English, Spanish, Portuguese, and French. Case studies had to include an agricultural context; studies on topics such as geophagy (soil eating; e.g., Rowland 2002), entomophagy, edible wild fungi, and local knowledge of soil biota in isolation from agriculture, e.g., Brazilian studies on myriapods (Costa-Neto 2006) and giant earthworms (Drumond et al. 2015), were not included.

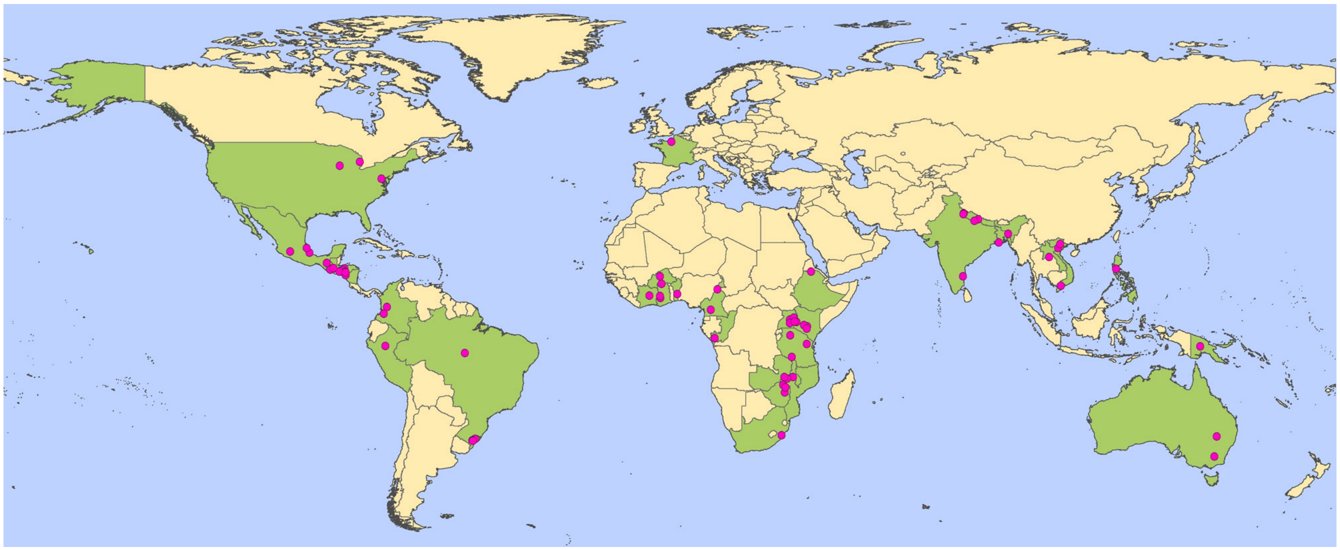
We found 60 studies that met our search criteria (see Table A1.1). Of these, around 47% had a substantial focus on soil biology or invertebrates; in the others, soil biota were often mentioned only briefly. The relatively small number of studies is likely a reflection of the minimal overlap between soil biology and the social sciences. Further, invertebrates are less well-studied than vertebrates in ethnobiology (Meyer-Rochow and Changkija 1997, Ratcliffe 2006) and in the conservation literature (Clark and May 2002), despite being orders of magnitude more abundant. Finally, there may be additional research on this topic in less accessible grey literature, such as local reports and dissertations that are not publicly available. Indeed, some of the grey literature accessed in this review contained extremely detailed insights from farmers on soil biological knowledge (e.g., Dix 1997, Nyeko and Olubayo 2005, Pincus 2015).

SYNTHESIS

Geographic, thematic, and taxonomic coverage

Geographically, research on farmer knowledge of soil fauna in agriculture is most prevalent in East Africa, Central America, and South and Southeast Asia (Fig. 1). One recent study was uncovered in Europe, with three from the USA and two from Australia. The geographic distribution may partially reflect the perceived importance of soil fauna in agriculture. The majority of the systems studied (n = 51) were exclusively smallholder agricultural systems (Table A1.1), where the management of soil biological fertility may be an important base for productivity.

Fig. 1. Geographic distribution of studies of farmers' perception and knowledge of soil fauna in agricultural contexts. The approximate location of individual studies is shown by the magenta dots. The 32 countries for which at least one piece of original research was found are denoted in green. Full bibliographic details of the studies included in the map are provided in the online Appendix to this paper.

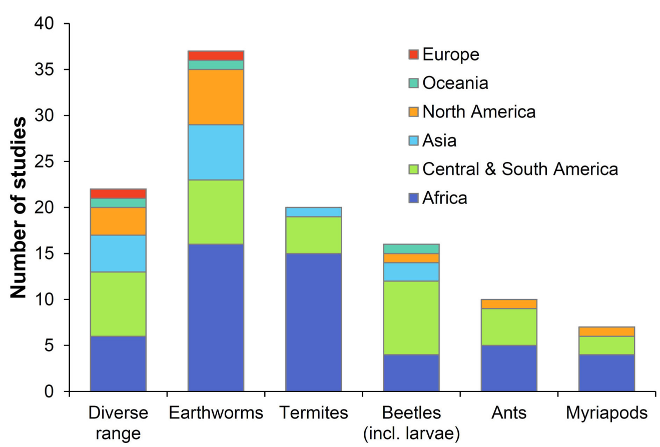


Local knowledge, joint investigation, and participatory research may be taken as a more legitimate path of agricultural enquiry by funding bodies in developing country contexts than in high-income countries. The mapped distribution may also reflect the location of institutions such as the Tropical Soil Biology and Fertility Institute (TSBF), with headquarters in Nairobi, Kenya, and field sites for global projects such as the Belowground Biodiversity Project (BGBD), including Brazil, India, Indonesia, Côte d'Ivoire, Uganda, Kenya, and Mexico.

Examining the primary research motivations (Table 1), half the studies were exploratory, conceptual, or methodological contributions, i.e., not applied research. Nearly one quarter of the studies, including four from high-income countries, were focused on developing locally relevant (often farmer-friendly) soil assessment or management tools. Thirteen studies were motivated by a desire to improve agricultural training, extension, or research. Two papers examined the potential for local soil knowledge to be formally recognized in national databases and agricultural development programs.

The majority of publications in the study (*n* = 35) included attention to multiple soil fauna taxa, while the remainder covered one taxonomic group (such as earthworms or termites; Fig. 2). Earthworms were a focal taxon in around 60% of studies, while termites figured prominently in a third of studies. Publications where a diverse range of soil invertebrates were explored (at least four taxonomic groups) were typically studies of ethnoecology (e.g., Sillitoe 1995, Gurung 2003), integrated pest management (e.g., Morales and Perfecto 2000, Mugerwa et al. 2011), or concerned with farmer views of all soil fauna (e.g., Grossman 2003, Pauli et al. 2012, Kipkorir 2015). Geographically, studies on termites were predominately from Africa, highlighting their importance in this region (Sileshi et al. 2009), studies on beetles and beetle larvae were concentrated in Central and South America, because of the economic importance of soil-dwelling scarab beetle larvae as crop pests (Dix 1997), while other taxa were more evenly distributed across global regions (Fig. 2). Farmers nominated the focal taxa in 62% of studies, researchers defined the taxa in 18% of the papers, and the remaining studies included joint definition (12%), or consisted of observations without consultation (8%).

Fig. 2. Broad taxonomic groups addressed in 60 studies of farmer knowledge of soil fauna, tallied by geographic region. Listed are broad taxonomic groups that were mentioned in some detail by at least seven studies.



Exploring themes using the *corpus-praxis-kosmos* complex

A number of distinct themes emerged from the reviewed research (Table 1). We explore these themes first in terms of the *corpus-praxis-kosmos* (*c-p-k*) complex, and second in relation to

Table 1. Primary research motivation and common themes addressed in 60 reviewed studies on farmer knowledge of soil fauna.

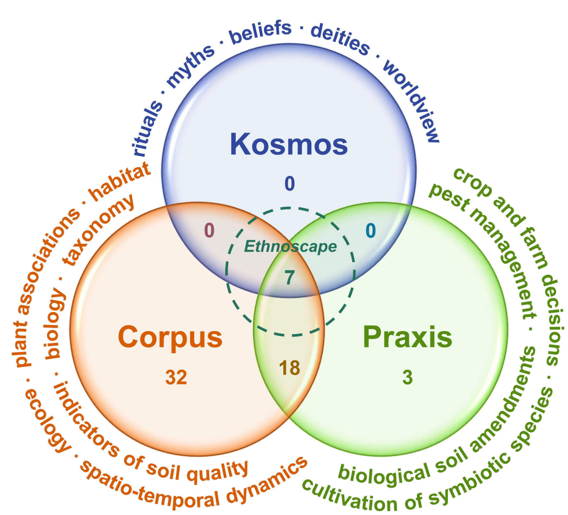
Primary research motivation[†]	Research in high-income countries[‡]	Research in low- and middle-income countries[‡]	Total
Exploratory, conceptual, or methodological contributions	1	29	30
Develop locally relevant soil quality/fertility management or assessment tools	4	10	14
Inform, improve, or evaluate agricultural research, extension, and training	1	12	13
Prioritize local knowledge to augment databases, development policies, and decision making	0	2	2
Assess sustainable resource use	0	1	1
Broad theme	Substantial focus on soil biota or invertebrates	Papers with a broader focus (e.g., soil quality)	Total[§]
Soil fauna as an indicator of soil fertility status	13	26	39
Knowledge comparison, recognition, validation, or integration	8	18	26
Detailed farmers' observations (e.g., on seasonal abundance, life cycle, preferred habitat, ecological interactions)	18	0	18
Integrated pest management	10	1	11
Direct use or manipulation of soil biota in agricultural management	7	4	11
Ethnoecology or folk taxonomy	9	2	11
Soil biological activity as part of local classification of soil types	0	6	6

[†]A single primary research motivation per paper was drawn from the abstract based on authors' categorization. Where the motivation was unclear in the abstract, the stated objectives in the introduction were used. Full description of study motivation or application in Appendix 1.
[‡]Income categories follow the *World Bank Atlas* definition (2015 fiscal year).
[§]Several papers addressed more than one broad theme, so that the total in the final column is > 60.

knowledge integration. The reviewed studies were scored according to whether any of the three domains in the *c-p-k* complex were examined, following Barrera-Bassols and Toledo's (2005) categorization. Few of the reviewed publications explicitly used an ethnoecological approach; the presence of each of the *c-p-k* domains within the studies was scored according to our interpretation of the reported findings. The numbers of studies in each category are presented in a Venn diagram based on Barrera-Bassols and Toledo's (2005) conceptualization (Fig. 3). Our analysis is based only on reported material; it remains possible that local knowledge of soil fauna encompassed other dimensions that were unexplored or undocumented by the authors of the studies.

The body of knowledge (*corpus*) held by farmers on soil biota was the most commonly elicited domain, with all but three studies documenting some element of *corpus*. Examples of knowledge held by farmers include local taxonomies of invertebrates; the level of detail elicited varied widely. The Nepalese Tharu people named 95 varieties of invertebrates from varying habitats (Gurung 2003), the Wola people of Papua New Guinea had 82 different names for invertebrates (Sillitoe 1995), and a study of Honduran folk entomology identified around 140 commonly known invertebrate taxa (Bentley and Rodríguez 2001), whereas other authors suggest that the farmers they worked with had limited traditional knowledge of soil biota (Pincus 2015), or had to be specifically prompted to divulge any information about soil fauna. Although farmers in some regions may have detailed knowledge of invertebrates and soil biota, deep knowledge may extend only to aspects of the soil biota that are easy to observe, or that are culturally or agronomically important (Bentley and Rodríguez 2001).

Fig. 3. Aspects of ethnoecology addressed by reviewed studies on farmer knowledge of soil fauna, based on the *corpus-praxis-kosmos* complex. The conceptual representation of the *corpus-praxis-kosmos* (or "knowledge-practice-belief") complex in ethnoecology is based on Berkes et al. (2000) and Barrera-Bassols and Toledo (2005). At the center of the three overlapping domains lies the "ethnoscape". The numbers in each section of the diagram refer to the number of original studies in our review (n = 60) that documented aspects of the *corpus-praxis-kosmos* complex. Curved phrases highlight the key elements and interactions mentioned by study participants that fall within each domain, based on broad categories put forward by Barrera-Bassols and Toledo (2005).



Another common theme within *corpus* was the presence of soil fauna as an indicator of soil fertility status (*n* = 39), or as a component of soil classification (*n* = 6; Table 1). The most common indicator taxa included earthworms, beetle larvae, termites, and ants. Often, the presence of earthworms, earthworm casts, and/or beetle larvae was widely thought to indicate productive land (e.g., Murage et al. 2000, Barrios and Trejo 2003, Saleque et al. 2008), but in other cases some or all farmers in particular locations believed earthworms to have deleterious or neutral effects on soils and crops (e.g., Sillitoe 1995, Ortiz et al. 1999, Birang et al. 2003, Saïdou et al. 2008). In some regions, farmers use the activity or abundance of particular taxa to classify soil types. For example, earthworms and termites are used by the Béte people of Côte d'Ivoire to aid in identification of subsoils because the soil fauna carry soil particles to the surface (Birmingham 2003). Several authors elicited detailed local observations of species (*n* = 18; Table 1), such as farmers' knowledge of life cycles, preferred habitats, and seasonal abundance (e.g., Dix 1997), mound morphology of different termite species (Malaret and Ngoru 1989, Nyeko and Olubayo 2005), and ecological interactions with tree species (Pauli et al. 2012, Kipkorir 2015).

In around one-third of cases reviewed, researchers elicited information on how farmers use information on the abundance or distribution of soil fauna for agricultural decisions (such as where or when to plant particular crops, or how to manipulate soil fauna for agricultural purposes); these were scored as examples of *praxis*. Eighteen studies documented both *corpus* and *praxis*; the three studies that described only *praxis* were observational studies that showed deliberate consideration of termite mounds in the spatial arrangement of smallholder fields in Zimbabwe (Carter and Murwiwa 1995) and Tanzania (Mielke and Mielke 1982), and the use of termites to rehabilitate degraded soils in Burkina Faso (Roose et al. 1999). Examples of how farmers might use soil fauna information in decision making include assessing whether soil management strategies are working over the short term (Desbiez et al. 2004), and using soil fauna abundance or community composition to determine when soil fertility is sufficient to commence cropping (Black and Okwakol 1997, Dawoe et al. 2012). Soil from termite mounds is used by Lao rice farmers as fertilizer (Miyagawa et al. 2011), a practice also reported from several locations on the African continent (Sileshi et al. 2009).

Deliberate use of soil fauna to improve soils has been documented in Africa and South America. Zaï practice from semiarid West Africa relies on the action of termites to dig galleries in degraded, crusted soil (attracted by organic matter placed in small pits by farmers), allowing water to infiltrate and providing nutrients for plants through the decomposition of organic matter (Roose et al. 1999). Variants of this traditional system have been examined experimentally by soil scientists, highlighting its effectiveness in soil rehabilitation (e.g. Mando et al. 1996, 1999). The Kayapó people of the Brazilian Amazon basin add soil from termite mounds and ant nests, along with live termites and ants, to mounds of mulch placed in shallow depressions. These mounds are tended and slowly evolve to become forest "islands" (*apêtê*) in the surrounding savanna over the course of decades, which are highly valued as refuges, sources of food, firewood, poisons, medicines, and materials for daily life (Posey 1985).

Several studies gave insight into strategies employed by farmers to reduce the severity of pest attacks by soil invertebrates (examples of *praxis*). Farmers in Honduras used crop rotation, ash application, and reliance on natural predators to deter white grub infestation (Pauli et al. 2012); similar practices were documented by Morales and Perfecto (2000) and Wyckhuys and O'Neil (2007) in central America. A variety of techniques to discourage termites from attacking tree crops were elicited from farmers in Malawi, Mozambique, and Zambia, including planting cuttings of a plant believed to attract termites in termite-infested areas, digging up the mound, and destroying the queen, applying wood ash in planting holes, and applying meat to attract predatory ants (Sileshi et al. 2008), while farmers in the rangelands of Uganda had a detailed understanding of the links between overgrazing, ecosystem deterioration, and heightened termite damage of pasture vegetation (Mugerwa et al. 2011).

Although seldom described in the reviewed studies, soil invertebrates can figure in local people's belief and spiritual systems (*kosmos*). For example, termites feature prominently in iconography in San rock art in Southern Africa (Mguni 2006), the "Honey Ant Dreaming" mural painted at Papunya in 1971 was the catalyst that started the famous Western Desert Australian Aboriginal Art movement (Carmichael and Kohen 2013), and scarab beetles were widespread in religion and cosmology in ancient Egypt (Ratcliffe 2006). The cosmological significance of invertebrates was touched on in seven reviewed studies. The Cakchiquel Maya of Guatemala believe they should share their corn with the animals, and for this reason they do not believe in killing invertebrate "pests" that may attack their sacred crop (Morales and Perfecto 2000). Elsewhere in Mesoamerica, the soil is conceptualized as a living being (Barrera-Bassols 2003, Barrera-Bassols et al. 2006), and earthworms figure in beliefs and myths as a "symbolic bridge of fertility and health between man and nature" (Ortiz et al. 1999:246). The only reviewed study of nonindigenous people to consider elements of *kosmos* indicated that Michigan farmers' worldview influenced their management strategies (organic or nonorganic) and the regard attached to "living soil" (Atwood 2010). Some cultures hold negative views of invertebrates stemming from overt or covert beliefs. The Tharu of Nepal believe "small living things," including insects, are a mistake in God's creation, while the Wola of Papua New Guinea attribute painful sores to earthworm bites (Sillitoe 1995). People's belief systems may have a clear link to perceptions of and values attached to soil fauna, which could have an impact on the uptake (or otherwise) of management strategies designed to foster improved soil health through greater biological activity.

Hybrid knowledge: comparing, validating, and integrating

Nearly half of the reviewed studies included some element of comparing or integrating different types of knowledge held on soil biota or soils (Table 1). Early papers in the field of ethnopedology tended to view knowledge gained by the scientific method as correct, with an emphasis on validating whether local knowledge reflected or correlated with scientific understanding, and could therefore be proven (Barrera-Bassols and Zinck 2003). More recent work acknowledges that an integrated approach, where multiple forms of enquiry are pursued, collaboration with local people is actively sought, and no particular type of knowledge is privileged as superior, is required to better understand the role that local cultural, social, and economic processes play in agricultural management (Barrera-Bassols and Zinck 2003). Most of the studies sampled for this review reflect the latter trend, which is perhaps due to the relative novelty of research on local knowledge of soil biota. Rationale for comparing or integrating knowledge included collaborative development of local indicators of soil fertility (Rousseau et al. 2013; see also Barrios et al. 2012); creation of locally appropriate soil maps through integrated knowledge (e.g., Saleque et al. 2008, Tesfahunegn et al. 2011); joint investigation of the life cycle and distribution of poorly understood soil-dwelling crop pests (Dix 1997); and assessing the similarities and differences among local and scientific understanding of soil biota in pest management and soil fertility (e.g., Price 2001, Ericksen and Ardon 2003, Saïdou et al. 2008).

Several papers examined farmers' understanding of the role of soil organisms in soil processes within the context of developing agricultural extension. In the Ashanti region of western Ghana, a large majority of interviewed farmers understood that soil fauna assist in the physical breakdown of organic matter and through this contribute to soil fertility, but a much smaller proportion appreciate their role in gas and water exchange (Dawoe et al. 2012). Arguably, comminution of organic matter is visible, whereas physical activity in the soil profile is not, reflecting Bentley and Rodríguez' (2001) assertion that deeper knowledge extends to soil-dwelling species that are easily observed. Similarly, Grossman (2003) found that although organic coffee farmers in Chiapas (Mexico) had a thorough understanding of organic matter decomposition, some important knowledge gaps existed in processes that farmers could not see, including nitrogen fixation, soil microbial activity, and mineralization. These studies highlight the importance of developing collaborative approaches to agricultural extension, where knowledge from a range of different sources and social-ecological contexts is seen as valuable for the development of sustainable agriculture.

A topic on which little research has been published is the use of soil biota as a potentially rich talking point around which to build knowledge interchange between farmers and researchers. Visible soil biota can give farmers immediate feedback on how their land management practices are working, while the use of narratives and guided use of appropriate technology can make the invisible visible, and facilitate the process of integrating knowledge. Recent research highlights this trend. For example, the L'Observatoire Agricole de la Biodiversité in France provides interested farmers with training on how to quantify elements of agricultural biodiversity (including litter and soil invertebrates) that relate to farm management (Deschamps and Demeulenaere 2015). In Uganda, farmers interviewed by Pincus (2015) were initially largely unaware of the role earthworms play in agriculture, but after attending training and participating in soil testing, over 80% of farmers viewed earthworm presence as an indicator of soil fertility. In the following paragraphs, we report several as-yet unpublished examples encompassing a diverse range of agroecosystems and cultural contexts to illustrate how this can work.

In Mexico, researchers have developed illustrated narrative booklets to discuss the consequences of different management strategies for vital plant symbionts including mycorrhizal fungi in roots and nitrogen fixing bacteria (Fig. 4). Land degradation is a serious problem in mountainous areas in Mexico that has resulted in decreased maize productivity and food insecurity. At the center of this problem is the loss of traditional crop diversity (intra- and interspecific) after the ill-informed adoption of technological packages including maize hybrids and chemical fertilization. Research suggests that the loss of locally developed crops and pulses of nutrients have diminished the diversity of well-adapted mycorrhizal fungi and nitrogen-fixing bacteria symbionts that developed with millennia of crop domestication by local Popoluca people (López-López et al. 2013, Sangabriel-Conde et al. 2014). The BioPop project (lead by author S. N.-Y.) developed a strategy to open discussion with farmers about this problem. A pair of illustrated publications including hybrid knowledge was handed to producers: a short story ("Don Erasmo's *milpa*"; Fig. 4A) and a triptych ("What is happening to the *milpa*?"; Fig. 4B). The short story is a first-person narrative of what happened to a farmer's soil, traditional knowledge, and food availability since technological packages arrived. The triptych is a symptom ("have you noticed that...?")-awareness ("what has happened is..."), that attempts to draw the links between traditional crop diversity, microbial symbiont conservation, nutrient use efficiency, and food security.

The Western Australian Wheatbelt region is an ancient, weathered landscape within a global biodiversity hotspot (Myers et al. 2000; Fig. 5). Broadacre farming of grain and livestock is the major land use. Author L. K. A. has been conducting workshops with farmers throughout the region for many years, most recently with the On-Farm Soil Health Monitoring project (Wheatbelt NRM et al. 2013). The goal of these workshops is to introduce farmers and landowners to the diversity of organisms in their soils, through on-farm soil monitoring methods such as extraction of soil mesofauna, and staining root samples to detect the presence of mycorrhizal fungi (Mahdi et al. 2016). Farmers are empowered to do their own experiments and analyses to support adaptive management. In the nutrient-poor soils of the Wheatbelt, mycorrhizal fungi can be important for crop growth. During workshops, farmer-friendly techniques for determining the presence or absence of mycorrhizal fungi in roots are demonstrated. Although these methods may not compare with the precision afforded by research laboratory images (Fig. 5), they are sufficient to help answer farmers' questions.

In the tropical dry forests of Nicaragua, soil arthropods were identified as an important local indicator of soil quality as part of collaborative, participatory research on land degradation. Between 2005 and 2010, author P. A. led an integrated planning process for pasturelands within the Nature Reserve Mesas de Moropotente in Nicaragua (Fig. 6). Land degradation due to overgrazing had caused economic losses in an area already affected by poverty. Stakeholders were brought together for a social multicriteria evaluation, with the intention of generating a constructive dialogue between local and scientific knowledge of the situation. Early on, improving soil quality emerged as a priority. There were substantial differences in the way that researchers and producers sought to describe and understand soil quality. Producers tended to aggregate different soil characteristics together into one complex soil quality indicator, while researchers focused on a series of independent, measurable soil parameters. Soil arthropods were identified by producers but were not initially associated specifically with soil. The presence

Fig. 4. Materials produced by the BioPop project for smallholder farmers in Mexico to illustrate plant symbionts including mycorrhizal fungi in roots and nitrogen fixing bacteria. A: "Don Erasmo's *milpa*" (a common term in Mexico and Central America for a smallholding where maize is the staple crop). B: "What is happening to the *milpa*?"

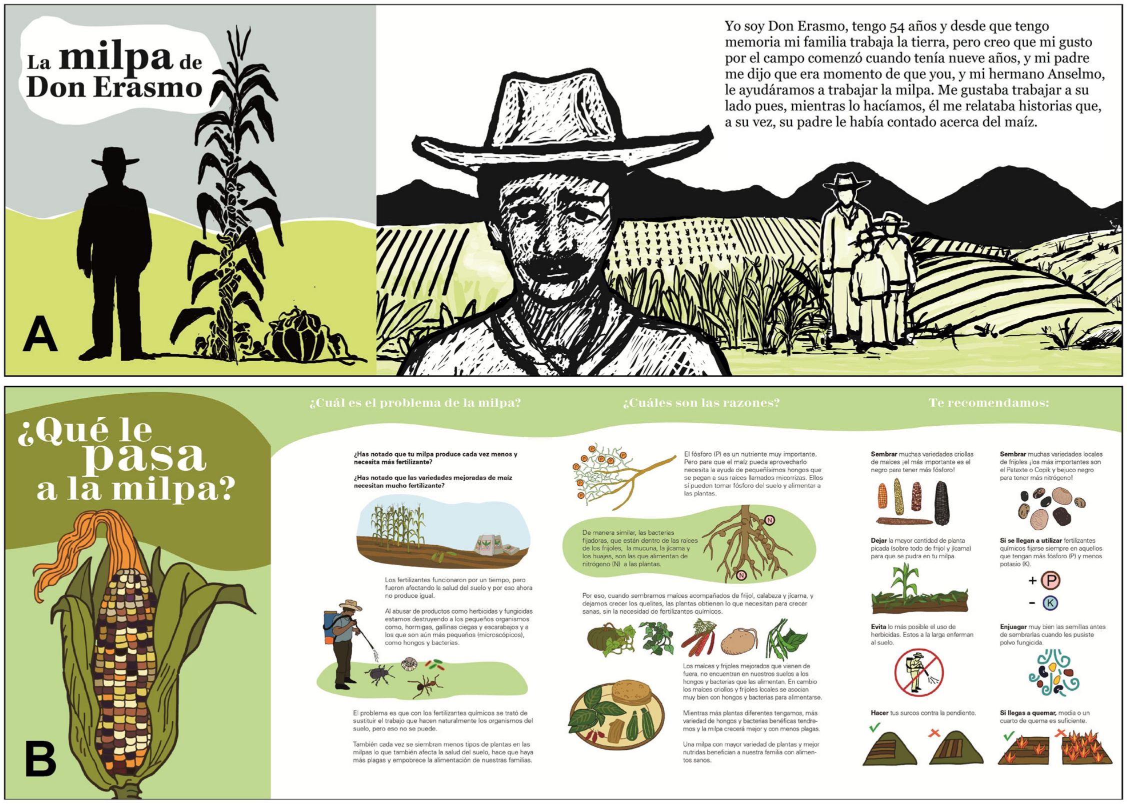


Fig. 5. On-farm soil health monitoring in workshops held in Western Australia to demonstrate farmer-friendly methods of soil biology assessment. A: Example images of roots stained using simple on-farm technique. B. Example research laboratory image (Photo by Bede Mickan). C: Locations of workshops held in 2013-2014. The green corresponds to the boundary of the southwest Australia biodiversity hotspot (Myers et al. 2000).

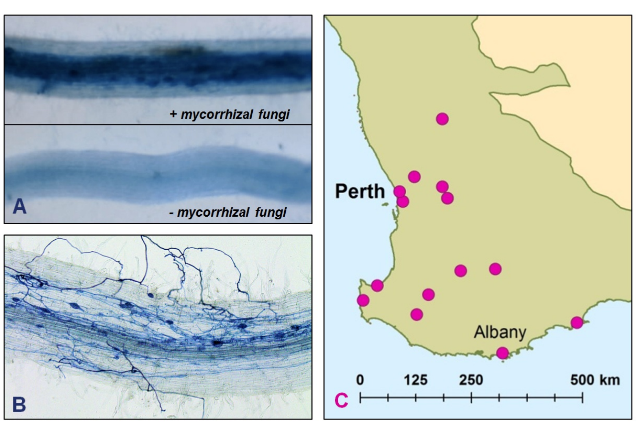


Fig. 6. Pasturelands of the Mesas de Moropotente, Nicaragua. The landscape depicted here is a nature reserve, which has suffered overgrazing and resultant land degradation. Inset depicts an epigeic beetle, one of the groups of soil fauna nominated by local farmers as an indicator of soil fertility.

of fauna at the soil surface was associated with healthy pastures, crops, and forests, and conveyed a sense of an ideal, pristine ecosystem, when there were no weeds and pastures were richly colored. As part of the dialogue, soil arthropods were eventually identified as indicators of soil fertility, through the effects of their faeces on soil aggregation. Producers granted access to their lands for soil sampling to quantify the diversity of epigeic fauna during the wet and dry season. The willingness of producers to support scientific sampling to evaluate indicators developed from discussion forums indicates the strength of local support for the process and research project.

CONCLUSIONS AND EMERGING AREAS FOR FURTHER RESEARCH

There is a potentially rich body of local knowledge on soil life, but one that is seldom tapped and often eclipsed by a focus on (a) other elements of the biota, or (b) soil physical and chemical properties. The lack of attention to this topic is particularly noticeable for high-income countries. Although farming systems in these countries may depart widely from the largely low-input, subsistence systems covered in this review, there is growing interest in biological farming and in more holistic views of soil health; recent work in Austria shows that farmers see soil as a key part of their identity, and many value "soil life" (Wahlhütter et al. 2016). Researchers investigating local soil knowledge and management should give consideration to the biological component of soil. In particular, researchers should direct attention not just to observations of soil biota (*corpus*), but also to how these organisms are considered in agricultural activities (*praxis*) and to the belief systems that influence agricultural practices and perceptions of soil life (*kosmos*). Further, there are few published data on local knowledge of the agricultural role of symbiotic microorganisms such as rhizobia and mycorrhizal fungi, or of other "invisible" organisms that have direct influence on agricultural productivity and soil fertility. We encourage collaborative partnerships among social scientists, soil scientists, farmers, and extension workers to jointly investigate these issues.

Our review raises questions about the local knowledge that has been lost, or is in danger of being lost. With the advent of synthetic inputs, technological solutions to increase yield, and greater productivity, coupled with out-migration from rural areas to urban zones, long-standing knowledge of the biological component of soil fertility could be eroded. The indigenous Guatemalan farmers interviewed by Morales and Perfecto (2000) feared their children would not continue with traditional practices and their knowledge would be lost. At the other end of the spectrum, many of the studies conducted in high-income countries highlighted the value of empowering farmers by developing locally relevant soil health assessments, reducing reliance on costly outside expertise. Although we did not explore gender as an influence on soil biological knowledge in this review, several authors noted gender-related differences (Saïdou et al. 2008, Sileshi et al. 2008, Zúñiga et al. 2013). The trend toward increasing feminization of agriculture in some global regions (Deere 2005) may also influence the knowledge that is retained, transmitted, and used in agriculture. Future work should consider how local soil knowledge may change over time in relation to socio-cultural and demographic drivers, as well as changes in land use and agricultural production systems.

In the last decades, science has made great strides in understanding the diversity and importance of soil life. However, general public awareness is said to be low (Wall et al. 2010), and interest from decision makers and government agencies is similarly subdued (Kust 2013). Our review shows that there are groups within the community who do value and understand soil life. However, aside from these few notable and fascinating exceptions, farmers are rarely deliberately or deeply consulted on their knowledge of soil organisms or soil biological processes, and research is rarely published in the peer-reviewed literature on the understanding or uptake of practices designed to enhance soil biological activity. A clear theme in many of the reviewed studies was that understanding and respecting how farmers view soil and soil life can help improve agricultural extension programs, soil management initiatives, and training in integrated pest management. Indeed, extension programs and farmer-led activities that incorporate soil biota exist (such as "microscope clubs" among grower groups in Australia), but they are rarely documented in the peer-reviewed literature. Collaborating with farmers, documenting their knowledge through participatory research, and presenting their views as equally important as those of soil scientists may also help to bridge the science-policy divide on this topic and add legitimacy to efforts to include soil organisms within broader legal and policy frameworks on soils.

Because of the sparse literature and the diverse, often site-specific investigative techniques used, much remains unknown about the depth of farmers' knowledge of soil biology. The integration of locally relevant knowledge with globally relevant scientific principles may help reduce risks associated with farming in marginal environments, or aid in adaptation to rapid environmental change (Oberthür et al. 2004). To aid adaptation to environmental and socioeconomic change, we urge researchers in this field to seek a clearer understanding of how famers value and perceive soil biota in agricultural production and sustainable land management. Properly applied, this knowledge will help deliver improved extension programs and management toolkits that are locally appropriate and tailored to farmers' needs.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/8597

Acknowledgments:

The BioPop project was financed by FOMIX (94427, CONACYT-Veracruz); "Don Erasmo's milpa" and "What is happening to the milpa?" were illustrated by Rafael Ruiz Moreno and coauthored by Jimena Mejía Alemán and Simoneta Negrete-Yankelevich. Funding for the Monitoring Soil Science On-Farm project was provided by the Australian Federal Government through Caring for Our Country to Wheatbelt Natural Resource Management Inc, Western Australia; partner organizations were The University of Western Australia (UWA), South West Catchments Council and the SPICE program at the Centre for Learning Technology (UWA). Bede Mickan provided the laboratory image of a root with mycorrhizal fungi. The project "Social multicriteria evaluation for the sustainable management and conservation of the Miraflor-

Moropotente Protected Terrestrial Landscape" was funded by the Catalan Agency for Development and Cooperation (ACCD) and the Autònoma Solidària Foundation (FAS) at the Autònomous Univeristy of Barcelona (Spain). Author NP wishes to acknowledge the valuable suggestions from participants in the first Global Soil Biodiversity Initiative (Dijon, France, 2-5 December 2014) and UWA colleagues M Tonts, S Prout, J Clifton, and F Haslam McKenzie for advice on previous versions of this paper. We are grateful for the constructive and insightful comments received on this manuscript from two anonymous reviewers.

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Appendix 1: Reviewed research on farmer knowledge of soil fauna in agricultural contexts.

Table A1.1: List of studies used to compile the worldwide map of reported local farmer knowledge of soil fauna in agricultural contexts (Figure 1)

Author	Focal Soil Fauna Taxa‡	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Adjei-Nsiah *et al.* (2004)	Earthworms, termites	Village of Asuoano, Wenchi District, Brong-Ahafo region, Ghana.	Indigenous Akan people, and migrant Lobi, Wala and Dagaba people. Smallholder farmers with main crops maize, cassava, yam, cocoyam, pigeon pea, plantain, cowpea and groundnut. Forest-savannah transitional agro-ecological zone.	Explore farmers' soil fertility management practices and their relevant social context (including comparing migrant farmers with local/Indigenous farmers), to ground future action research in the needs of the local farming community.
Ali (2003)	Earthworms	Damarpota village, floodplain of the Betravati (Betna) river, southwestern Bangladesh	Smallholder saline wet rice ecosystem; tropical monsoon climate with three cropping seasons. Main crops three varieties of rice, plus jute, vegetables and oilseeds.	Quantifying farmers' knowledge and comparing with scientific data to provide evidence that farmers' substantial knowledge should be used in agricultural development policies and in national scientific databases.
Atwood (2010)	Multiple	'Thumb' region of Michigan state (Huron, Sanilac, Tuscola and Lapeer counties), USA	Family farms growing multiple crops including soybeans, corn, sugarbeets, dry beans, and winter wheat, with some livestock	Compare and characterise the worldviews of organic and non-organic farmers through their observations of crop and soil health, perceptions of soil quality indicators and agricultural management information channels.
Audeh *et al.* (2011)	Multiple	Localities surrounding town of Canguçu, Rio Grande do Sul state, Brazil	Smallholder tobacco farmers in environmentally sensitive areas with shrub vegetation	Promote soil quality knowledge and derive a set of indicators to evaluate the effect of land use, management and soil conservation
Barrera-Bassols (2003)	Multiple	Lake Pátzcuaro basin, central Mexican volcanic highlands, Michoacán State, west Mexico	Purhépecha people. Smallholder agriculture based on milpa production, main crop maize. Temperate subhumid to cold humid climate.	Ethnopedological study with a view towards understanding decision-making by local people. Extremely detailed covering soil taxonomy and ethnoecology.
Barrios and Trejo (2003)	Earthworms	Tascalapa watershed, Yoro, Central Honduras	Smallholder hillside farmers using 'slash and burn' agriculture to produce maize and beans.	Description of approaches for eliciting local soil knowledge using case studies with view to developing integrated soil management based on local and scientific knowledge
Bentley and Rodríguez (2001)†	Multiple	Rural Honduras, further detail not specified	Honduran *campesinos*, further detail not specified.	Development of conceptual framework for understanding folk entomological knowledge using case study approach
Birang *et al*. (2003)†	Earthworms	Humid forest, southern Cameroon	Beti people of southern Cameroon. Smallholder agriculture using 'slash and burn' cultivation of forest and fallow. Mixed crops including groundnut, cassava, maize, plantain, cocoyam and cacao.	Ascertaining 'baseline' farmer perceptions and knowledge as a means of predicting local attitudes towards alternative farming systems.
Birmingham (2003)	Termites, earthworms	Equatorial forest zone, southern Côte d'Ivoire and savannah zone, northern Côte d'Ivoire	Bété people of the equatorial forest zone and Senufo people of the guinea-savanna zone. Bété practice slash-and-burn for food crops (staple crop rice), and tree cash crops including coffee and cocoa. Senufo practice longer fallows with food crops (staple crop rice), and cotton cash crop	Describe local knowledge of soil types and compare with scientific data with view to improving research and extension efforts.
Buthelezi (2010)	Earthworms, 'soil mesofauna'	uMbumbulu region, KwaZulu-Natal province, South Africa	Smallholder farmers cultivating *amadumbe* (taro), maize, sweet potatoes and potatoes	Investigate the use of Indigenous knowledge in farming, as well as farmers' perceptions and assessments of soil fertility (scientific measurements of soil properties were also made)

Author	Focal Soil Fauna Taxa[‡]	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Carter and Murwira (1995)	Termites	Mutoko communal area, northeast Zimbabwe	Smallholder agriculture, mixed crops including maize, millet, sorghum, cowpeas, groundnuts, sunflower, rice and vegetables. Cattle grazing on communal lands.	Exploration of the methods used by farmers to exploit edaphic variability for crop and soil management.
Cerón Rengifo *et al.* (2003)	Multiple	Potrerillo watershed in Cauca, Colombia; Andes Cordillera (1400-1500 masl)	Smallholder farmers cultivating coffee, banana, yucca, maize, beans, green tomato, sugar cane and some fruits	Relate local soil classifications to measurements of chemical, physical and biological characteristics.
Chandola *et al.* (2011)	Beetle larvae	Bageshwar district of Uttarakhand state, India	Smallholder farmers growing irrigated rice, and rain-fed crops (wheat, dry rice). Western Himalayan region.	Document traditional and Indigenous pest management practices that do not rely on application of synthetic chemicals
Dai Trung *et al*. (2008)	Earthworms	Tan Lac district, Hoa Binh province, mountain karst in northern Vietnam	Muong ethnic group. Smallholder agriculture on small plots on mountain slopes and in stream valleys, staple crop rice.	Documentation of ethnopedological knowledge and validation of local soil fertility indicators using scientific data
Dawoe *et al*. (2012)	Multiple	Ashanti region, semi-deciduous forest, western Ghana	Majority Indigenous Akan-speaking people. Smallholder agriculture, crops include maize.	Understanding and integrating farmer and scientific knowledge to facilitate improved nutrient cycling.
Desbiez *et al*. (2004)	Multiple	Pakuwa village, Parbat District, mid-hills of western Nepal	Brahmin and Chhetri ethnic groups. Terraced agricultural land ranging 850-1500 m, including: ‘lowland’ irrigated terraces, ‘upland’ rainfed terraces, kitchen gardens and pasture. Main crops wheat, potatoes, maize, rice, millet.	Understanding and integrating farmer and scientific knowledge to facilitate improved soil fertility management.
Deschamps and Demeulenaere (2015) [†]	Multiple	Departments of Vendée, Marne and Eure, France	Farmers participating in the *L'Observatoire Agricole de la Biodiversité* (Agricultural Biodiversity Observatory), a voluntary citizen science and ‘participatory ecology’ program under the guidance of the Ministry of Agriculture	Understand farmer adoption of observations of agricultural biodiversity (measures included the abundance of earthworms to indicate soil quality, and the number of terrestrial invertebrates accumulating under planks of wood left on the ground to indicate resilience to pest attacks).
Dix (1997)[†]	Beetle larvae	Chilasco village, highlands of Baja Verapaz department, eastern Guatemala (1840 masl)	Smallholder growers of broccoli (cash crop) and corn; secondary crops include beans, potatoes, red peppers, cabbage, squash. Transition zone between mixed conifer and broadleaf cloud forest in the buffer zone of the Sierra de las Minas Biosphere Reserve.	Determine the relationship between pest (white grub / beetle larvae) abundance and organic matter amendments, guided by farmers’ practices and beliefs as to what influenced the presence of white grubs, with view to developing more effective integrated pest management strategies.
Ericksen and Ardon (2003)	Earthworms, beetles	La Lima watershed, central Honduras	Farmers of mixed Indigenous and Spanish descent. Mixed smallholder agriculture including beans, corns, horticultural crops with some coffee groves (some shaded with fruit trees) and pastures.	Comparison of interpretation of local farmers’ knowledge and soil scientist’s knowledge to find ‘common ground’ between two understandings (not validate)
Grossman (2003)[†]	Multiple	Highland and lake regions of Chiapas state, Mexico	Indigenous Mayan peasants in highland region (Tzeltal and Tzotzil speakers) and Spanish speakers in lake region. Small-scale organic coffee producers.	Assessment of farmer understanding of soil fertility enhancement processes in decision-making and experimentation in context of assessing gaps in knowledge for training programmes.
Gruver and Weil (2006)	Earthworms	States of Maryland, Delaware, Pennsylvania, Virginia, West Virginia, Mid-Atlantic USA	Farmers interested in soil conservation. Range of farm sizes included e.g. cash grains 20-2800 ha, dairy 70-2260 ha. Mixed enterprises including grains, vegetables, hay, livestock.	Participatory definition of soil quality benchmarks using farmer judgements of soil quality and individual soil parameters.

Author	Focal Soil Fauna Taxa‡	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Gurung (2003)†	Multiple	Dang-Deukhuri district, subtropical lowlands (Terai) of Nepal	Tharu people. Smallholder agriculture, main crops include maize, rice, wheat, mustard seed. Livestock reared at homesteads.	Ethnoentomological study with application to improve efficacy and acceptance of pest management programmes.
Joshi and Singh (2006)	Earthworms, beetle larvae	Eight villages from Almora and Nainital districts, representing valleys and uplands in the hills of Uttaranchal, western Himalayas, India	Smallholder low input systems with crops, horticulture, livestock, forestry and animal husbandry	Document traditional agricultural practices in low-input agricultural system.
Kelly *et al*. (2009)	Earthworms, beetles	Billabong catchment, southern New South Wales, southeast Australia	Dryland broadacre cropping and grazing, further details not specified.	Understand how farmers use soil indicators to inform management decisions with view to improving soil health projects and empowering farmers.
Kipkorir (2015)†	Multiple	Six villages surrounding Kiberashi Sentinel Site, *miombo* woodlands, Tanzania	Smallholder mixed subsistence farming; main crops include maize and beans, with mixed livestock including cattle, goats, sheep, donkeys	Elicit farmers' knowledge of indigenous tree species, soil macrofauna and their interactions, and use these relationships to guide scientific sampling of soil properties and soil fauna around trees.
de Lima *et al*. (2011)	Earthworms	Camaquã county, coastal plains of Rio Grande do Sul state, southern Brazil	Rice farmers cultivating fields ranging from 2-500 ha; majority small landholders descended from German and Polish settlers arrived late 19th C. Families were formerly landless and granted land from the early 1960s.	Determine locally important soil quality indicators and their use in land management.
Lobry de Bruyn and Abbey (2003)	Multiple	Northwest cropping region of New South Wales, southeast Australia	Range of farm sizes from 66 to 30 000 ha. Grain-growing region. Representative sample of farmers in the region.	Developing a prototype collaborative farmer's soil health checklist with aim of empowering farmers to be more self-reliant.
Mairura *et al*. (2007)	Multiple	Chuka and Gachoka divisions, central Kenya highlands	Intensively managed smallholder farms typically with cereal-legume intercrops for home consumption, market crops, livestock and kitchen gardens.	Determine farmers' perceptions of soil quality and soil management practices, and compare with soil physical and chemical properties to assess local soil fertility indicators.
Malaret and Ngoru (1989)†	Termites	Mbiuni location, Machakos district, Kenya	Akamba people. Smallholder farmers growing maize intercropped with beans, cowpeas or pigeon peas, and grazing. Indigenous trees left within crop lands for fodder, timber and fuel. Transitional zone from sub-humid to semi-arid climate.	Determine scope and relevance of Indigenous knowledge of termite ecology for pest control in agricultural and agroforestry production systems.
M'Biandoun and Olina Bassala (2007)	Multiple	Four villages in northern Cameroon (Mowo, Gadas, Mafa Kilda, Fignolé)	The four villages differ in ethnicity, climate, geomorphology & soils and population density. Doayo, Mafa, Moundang and Mofou people. Smallholder farmers with main crops including cotton, maize, sorghum, *muskwari* (dry season sorghum). Annual rainfall between 700-1500 mm.	Understand how farmers assess the fertility of their land and capacity of farmland to produce crops; criteria included biophysical indicators and the productivity of labour for particular crops.
Mielke and Mielke (1982)	Termites	Southwest Tanzania	Smallholder chitemene agriculture (slash-and-burn cultivation with pollarded trees; fields have a circular form). Detail on farmers not given.	Statistical analysis of spatial association between termite mounds and field locations, emphasising that the importance of termites in traditional agricultural practices is at odds with recent efforts to 'control' termites.

Author	Focal Soil Fauna Taxa[‡]	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Miyagawa *et al*. (2011)[†]	Termites	Dong Khuai village, Vientiane Plain, Laos	Lao speakers. Smallholder agriculture, rainfed lowland rice production (paddy fields and upland areas) with some fish farming adjacent to paddy fields (termites used as fish feed).	Determine the sustainability of the use of termite mounds by rice farmers.
Morales and Perfecto (2000)[†]	Multiple	Community of Patzún, Chimaltenango Department, Guatemalan highlands (2000[+] masl)	Cazchiquel Maya farmers. Smallholder agriculture based on traditional *milpa* (maize polyculture with combinations of climbing beans, fava beans and squash) and non-traditional export crops (broccoli, snow peas, zucchini)	Understanding farmers' agricultural knowledge as first step to design a more participatory, effective research process in integrated pest management.
Mugerwa *et al*. (2011)[†]	Termites	Nakasongola District, semi-arid rangelands of central Uganda	Smallholder farmers involved in livestock grazing (majority cattle) with some crop production	Investigate farmer's traditional ecological knowledge of termites to develop appropriate termite control strategies.
Murage *et al*. (2000)	Earthworms, beetle larvae	Kiambu District, central Kenya highlands	Smallholder agriculture, mixed crops (cereal-legume intercrops for home consumption) established in cleared afromontane forest or evergreen bushland.	Identification of indicators of soil fertility status (based on soil sample analysis) consistent with farmers' perceptions of soil fertility with view to developing simple indicators of soil fertility to assess land management interventions.
Nezomba *et al*. (2015)	Millipedes, earthworms, ants	Nyahava ward in Makoni and Goto ward in Hwezda, eastern Zimbabwe	Smallholder farmers growing maize as principal crop, with food legumes (e.g. groundnut) and cowpea.	Investigate farmers' knowledge of soil degradation and the commonly used local diagnostic indicators, as an entry point for developing locally-appropriate integrated soil fertility management using legume cover crops
Nhamo (2007)[†]	Multiple	Shamva (north-eastern Zimbabwe) and Zimuto areas (Southern Zimbabwe)	Smallholder farmers operating within a communal tenure system. Mixed farming with crops (maize for subsistence, cash crops, small grains, legumes) and livestock. Open *miombo* savanna vegetation from sub-humid and semi-arid climates.	Understand how the farmers' knowledge of soil fauna was linked with patterns of residue utilisation by farmers in conservation agriculture.
Nyeko and Olubayo (2005)	Termites	Tororo district, eastern Uganda	Majority Japadhola and Itesot ethnic groups, smallholder farmers. Staple food crops cassava, millet, maize and sorghum, with oil seed crops such as groundnuts, sesame and sunflower, as well as beans, cowpeas. Mixed livestock. Dry sub-humid lowlands (900-1300 mm bimodal rainfall). Agroforestry promoted in district for wood production, soil fertility management, tree products, fodder production.	Document and examine farmers' indigenous knowledge of termites (as a little explored topic), with the aim of developing and promoting locally appropriate and relevant integrated termite management in agroforestry.
Ortiz-Espejel *et al*. (1999)[†]	Earthworms	Northern, central and southern regions of Veracruz State, Mexico	Totonaco, Nahua and Zoque-Popoluca ethnic groups. Smallholder agriculture, further detail on farming systems not detailed.	Ethnological survey of knowledge of earthworm activity in relation to soil fertility, with a view to understanding whether local beliefs will support management practices focused on increasing earthworm populations.
Ortiz-Espejel *et al.* (2009)[†]	Earthworms	Four countries: Mexico, state of Veracruz (localities Papantla, Vega de Alatorre y Medellín), Peru (Yurimaguas), India (Yarpadi) and Congo (Niari Valley)	Pastures under management by indigenous people in each location.	Understand whether farmers' traditional knowledge relates earthworms to soil fertility.

Author	Focal Soil Fauna Taxa‡	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Pauli *et al*. (2012)	Multiple	Lempira Department, tropical dry forest on rugged terrain (~400-900 masl), southern Honduras	Farmers of mixed descent (Indigenous Lenca and Spanish colonists). Smallholder agriculture based on slash-and-mulch of *milpa* (maize, beans, sorghum, mixed livestock)	Understanding how farmers incorporate knowledge of native species and ecological processes into land management, with view to deriving principles for promoting high-biodiversity farming systems elsewhere.
Payton *et al*. (2003)	Termites	Lowlands of Sukumaland, Lake Victoria catchment, northwest Tanzania	Sukuma ethnic group (Tanzania) and Iteso people (Uganda). Smallholder agriculture, main crops maize, sorghum, cowpeas, groundnuts with some rice and cotton.	Exploration of methods for eliciting Indigenous soils knowledge and integrating Indigenous and scientific knowledge for soil survey and mapping.
	Earthworms	Lake Kyoga catchment, southeast Uganda		
Pincus (2015)	Earthworms	Villages surrounding Nkokonjeru town, Lake Victoria Crescent region, Uganda	Smallholder farmers (Baganda people) growing a mix of subsistence (maize, cassava, potatoes, groundnuts, vegetables) and cash crops (banana, coffee), with some livestock. Experimental plots growing *nakati* (*Solanum aethiopicum*), an indigenous leafy green vegetable.	Understand the similarities and differences between farmers' and scientists' knowledge and perceptions of integrated soil fertility management (ISFM), through designing educational program to teach ISFM principles to farmers, and interviewing farmers before and after taking part in the program.
Posey (1985)	Termites, ants	Indian Post of Gorotire, largest of the northern Kayapo villages, Amazon Basin	Indigenous Kayapó cultivating forest 'islands' (apêtê) within campo/cerrado (tropical savannah) ecosystem, Brazilian Amazon Basin.	Document forest management practices of the Kayapó, situated within an ethnoecological framework. Emphasises importance of indigenous knowledge for conservation and productivity.
Price (2001)†	Multiple	Central Luzon, Philippines	Smallholder agriculture, rice cultivation.	Determining change in pest management knowledge before and after two different interventions.
Romig *et al*. (1995)	Earthworms	Southeast Wisconsin, USA	Conventional and low-input cash grain and dairy farms ranging in size from 80 to 2,200 ha; participants associated with a research project on integrated cropping systems	Understanding farmers' assessment of soil health, with view for development of soil health scorecard based on farmers knowledge and potential for integrating knowledge.
Roose *et al.* (1999)†	Termites	Yatenga and Passore provinces, Mossi plateau, northern Burkina Faso.	Subsistence farming based on cereals, peanuts, sesame and niébé (cowpea). Sudano-Sahelian shrub-savanna with 6-8 month dry season.	Determine potential of 'zaï' practice to restore soil fertility in degraded areas (method relies on action of termites to break up soil crusts, create galleries and allow water infiltration.)
Rousseau *et al*. (2013)†	Multiple	Chinandega department, tropical dry forest region of western Nicaragua	Smallholder agriculture encompassing a range of land use management, including traditional cropping, slash-and-mulch agroforestry and silvopastoral systems. Maize, beans.	Identification of soil invertebrates that could act as indicator taxa of soil quality with a view to evaluating land management impacts.
Saïdou *et al*. (2004)	Earthworms	Atacora and Savé regions of Benin	Majority Ditammari ethnic group (Atacora) and Tchabé and Peulh people (Savé), with other ethnic groups and migrants. Smallholder agriculture with crop rotation and intercropping up to four years after forest clearance, followed by planting cashew trees. Crops include yam, cotton, groundnut, sorghum, maize, cowpea, cassava and *egusi* melon.	Understanding how farmers have adapted cropping systems to the local environment (including local experimentation) with view to developing interactive research framework for testing effectiveness and applicability of local innovations not well understood by conventional science.
Saïdou *et al*. (2008)†	Earthworms	Transitional agro-ecological zone of Benin	Indigenous Tchabé people and migrants from elsewhere in Benin. Earthworm abundance sampled in smallholder fields planted with cassava, egusi melon, cowpea and maize.	Participatory research on farmer perceptions of earthworm activity in different crops.

Author	Focal Soil Fauna Taxa‡	Location	Description of people and agroecosystem	Practical application or underlying motivation of study
Saleque *et al*. (2008)	Earthworms, mole crickets	Moulovibazar and Habiganj districts, eastern Bangladesh	Smallholder rice production with three growing seasons per year.	Compare farmers' perception of soil fertility with laboratory soil tests to develop an improved nutrient management programme based on both views.
Schiavon *et al.* (2015)†	Multiple	District of Rincão da Caneleira, Morro Redondo, Rio Grande do Sul, Brazil	Family farm practising 'ecological' horticulture	To determine the potential use of local knowledge for assessing the influence of management practices on soil fauna
Sileshi *et al*. (2008)†	Termites	Central and southern Malawi	Majority Chewa and Ngoni ethnic groups. Smallholder agriculture (staple crop maize) with pilot study of an agroforestry development project	Understanding farmers' Indigenous knowledge as basis for constructive collaboration in pest management
		Northern Mozambique		
		Eastern Zambia		
Sillitoe (1995)†	Multiple	Haelaelinja region, Was (Wage) river valley, Nipa District, southern highlands of Papua New Guinea	Wola people. Montane forest and cane grasslands. Shifting cultivation of gardens; some maintained for decades. Major crop sweet potato.	Ethnoscientific investigation into local knowledge of organic matter decomposition to further understanding of this understudied topic.
Tabu *et al*. (2003)†	Multiple	Kabras division, western Kenya	Smallholder maize/sugarcane cropping system in densely populated area.	Identification of soil macrofauna abundance and diversity in farmer-perceived soil fertility niches.
Tesfahunegn *et al*. (2011)	Earthworms	Mai-Negus catchment, Tigray region, northern Ethiopia	Smallholder agriculture with farmers representing a range of self-identified wealth categories. Major crop teff (*Eragrostis tef*) with pasture.	Local community diagnosis of soil quality to assess the contribution of local knowledge to strategies for sustainable developing decision-making, in context of scarce scientific information and relevance of local information.
Van Dang (2007)	Earthworms	Thai Nguyen region, northern mountains of Vietnam	Tea production as a cash crop in upland regions.	Identification of appropriate indicators for soil quality assessment using quantitative and qualitative (local knowledge) approaches with view to improve management.
Van Mele *et al*. (2001)†	Multiple	Mekong Delta, southern Vietnam	Mango orchards, two-thirds were <0.5 ha in size.	Understanding farmers' knowledge, perceptions and practices in pest management with view to improving management practices and pesticide use.
Wyckhuys and O'Neil (2007)†	Multiple	Upper Choluteca watershed, southeast Honduras	Smallholder farmers representative of rural Honduran villages. Subsistence farming based on maize, with some coffee and vegetable production.	Determine role of local knowledge in pest management and understand role of training in influencing knowledge.
Zúñiga *et al*. (2013)†	Earthworms	La Vieja River watershed, west central Colombia	Mosaic of land use patches including pastures, coffee, sugar cane, plantain, cassava, fruit trees, shaded coffee, forest and native bamboo.	Documenting farmer perceptions of earthworms, and integrating local and scientific knowledge to facilitate communication and education.

Notes:

† Denotes paper with a substantial focus on soil biology or invertebrates

‡ Focal soil fauna taxa only mentioned for summary purposes. See main text for indication of which papers mentioned other elements of the soil biota such as fungi and bacteria. 'Multiple' means four or more different taxa were addressed in some detail. Note that for many papers, soil biota were not the primary focus of the paper; this column highlights the soil fauna taxa that were mentioned by the authors

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