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Science and user-based co-development of a farmland earthworm survey facilitated using digital media: insights and policy implications

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Summary

Science-farming partnerships can improve our understanding of how land management behaviours sustain or enhance life-sustaining soil ecosystems. However, it remains a challenge to establish partnerships between researchers and practitioners that complement the ways in which farmers acquire and value knowledge, and can also advance soil science. A pilot study was conducted to explore these issues in relation to earthworm monitoring. It showed that farmers were interested in comparing their field results to research experiments to inform their decision making. Social media was used to support farmers' earthworm monitoring schemes, with concomitant sampling of research experiments to create capacity for shared learning. Constructive feedback from the scientific community was sought using an online questionnaire. An Autumn 2018 survey generated 152 field analyses from farmlands in England, and 48% participants' fields and the research experiment showed no evidence for earthworms being widespread and/or the presence of all three ecological groups of earthworms. A Spring 2019 survey generated earthworm population data from farmland soils around the world, amassing 11,464 earthworms assessed over 2,200 hectares in the UK. A total of 12 scientists (from 30 questionnaire invitations) volunteered their time and expertise to support the survey. Conclusions helped to prioritise future improvements in earthworm monitoring, which should include photographs of earthworms for verification of the data, long-term monitoring, and integration with soil properties. Most (83%) perceived this earthworm survey would likely improve farmland soil health and so would recommend its use in the UK. The survey is being independently taken forward and used as a metric by both private and public stakeholders, demonstrating authentic knowledge transfer in soil science.

Keywords

Earthworms, social media, civic science, citizen science.

1 | Introduction

Earthworm burrowing behaviours primarily influence soil structure, with consequences for water, gas and root movement in soils. Earthworm feeding behaviours influence nutrient cycling and plant disease incidence; and their trophic position influences predator populations, pollution transfer and parasite transmission (Edwards & Bohlen, 1996). Earthworms have global cultural significance, including symbolic connections of people to soils (Pauli *et al.*,

2016) and as indicators of soil fertility (Zúñiga *et al.*, 2013). The abundance of earthworms is positively correlated to crop productivity (van Groenigen *et al.*, 2014)). Earthworm monitoring influences individual and group behaviours: perceptions of increased earthworm abundance under no-tillage soil management have been instrumental in the adoption of no-tillage practices in Europe despite productivity constraints (Lahmar, 2010). In South America, no-tillage farmers have formed 'worm clubs' and used the earthworm as their emblem (Brown *et al.*, 2003). Earthworm monitoring is a high-leverage behaviour in soil management, but can it be made rigorously quantitative?

Soil management, specifically tillage intensity, was first shown to influence earthworm community structures on the Rothamsted long-term experiments in the 1930's (Evans & Guild, 1948), but earthworms were first categorised into 'ecological groups' with respect to their predominant feeding and burrowing behaviours in the 1970s (Bouché, 1977): epigeic types are surface dwelling, plant-litter feeding; endogeic types are topsoil burrowing, geophagous; anecic types construct deep, vertical burrows, and collect plant-litter from the soil surface to plug the top of their burrow, creating middens. The presence of all three types can be considered as indicating a functionally intact system (Ritz, 2021). Conventional tillage, e.g. ploughing/power-harrowing, reduces populations of plant litter-feeding epigeic and midden-forming anecic types (Chan, 2001; Briones & Schmidt, 2017), even causing local extinction (Kladivko *et al.*, 1997), but it can increase topsoil dwelling endogeic earthworm numbers by increasing their food supply through soil mixing (Chan, 2001). Tillage-sensitivity has been used to 'score' whether fields are functionally intact, i.e. contain earthworms from all three ecological types (Stroud, 2019).

If land management is defined as a knowledge-based system, its functioning depends on the degree to which it fosters expert behaviours (applying knowledge in context) and connects people experientially with the consequences of their actions. Decision theories conceptualise knowledge as perfect (optimisation) or imperfect (uncertainty) (Gigerenzer & Gaissmaier, 2011). The aim of optimisation is to quantify risk, which requires a perception of perfect knowledge so that the optimal solution can be calculated via known or reliably estimated probabilities (rational decision theory, e.g. Bayesian algorithms). In contrast, real-world decisions are made under uncertainty (imperfect knowledge). To date, just 1.4% of agri-environmental publications are based on such information systems or 'Heuristics' (Wyckhuys *et al.*, 2018).

Adopting decision strategies based on heuristics (to learn or discover for oneself) rather than optimisation could better support the development of Government-demanded policies for sustainable soil management in England and Wales by 2030, currently underpinned by a weak evidence base (Parliament, 2006). Research has shown that UK farmers describe their soil management in terms of response to tillage, suggesting little prior soil examination with implications for runoff/erosion (Ingram *et al.*, 2010). These problems are exacerbated by negative experiences when exploring reduced tillage systems including peer criticism, technical difficulty, isolation and lack of support (Ingram, 2010). Some of these problems have been mitigated through farmers' use of social media whilst developing reduced tillage practices, but surveys continue to generate responses such as "*I feel disengaged with the science community, they don't understand complexity" … "farmer to farmer learning is a powerful tool whilst there is a whole lot of science paperwork out there, but it is on a shelf somewhere*" (Skaalsveen *et al.*, 2020). More effective science-farming partnerships are necessary if we are to improve our understanding of how behaviours sustain or enhance the life-sustaining components of soil ecosystems.

The aim of the research reported here was therefore to use a heuristic approach to explore the potential of earthworm surveys to inform better soil management. This required an unconventional reporting style to accommodate the process of social innovation. It was hypothesised that: (1) farmers would be interested in the earthworm population 'scores' of fields they had selected for sampling; (2) as a survey only supports a single-user action, digital integration would facilitate collaboration and communication; (3) researchers would be interested in influencing the survey design to make it meaningful to soil science.

2 | Materials and methods

2.1 | Social media engagement

A Twitter account (@wormscience) was established and used to share images, observations and research papers. Virtual engagement with agricultural stakeholders involved using Twitter features such as 'Following' (900 accounts by 2018), 'Retweets' and 'Likes'.

2.2 | Farmland earthworm survey

The method was to dig and survey five soil pits (20 cm × 20 cm × 20 cm, hand-sorted) per field. In 2017 this was done by the first author on farmer's fields. In 2018–2019 this was done by the participating farmers. Earthworms were counted, and the mature (clitellate) earthworms identified by their ecological group (epigeic, endogeic or anecic). The presence/absence of middens (made by anecic *Lumbricus terrestis* earthworms) was also noted.

2.3 | Earthworm survey (Autumn 2017)

A general meeting between the authors (and colleagues) and the Rothamsted Farmer Network had highlighted an interest in earthworm surveys. This resulted in surveying farmers' fields together, with informal conversations about information needs. For example, there were questions about the earthworms on the Broadbalk Wheat Experiment at Rothamsted to aid interpretations. This informed the need for an earthworm and pesticide survey of Broadbalk.

Information about the Broadbalk long-term Wheat Experiment is freely available (Open Access) via the Electronic Rothamsted Archive, e-RA (e-RA, 2018). Briefly, the experiment started in 1843 and is located at Rothamsted Research, Hertfordshire, U.K. (51.8081N:0.3752W). The soil is classified as a Chromic Luvisol, consisting of a flinty clay loam to silty clay loam. Earthworms were assessed on sections 0, 1, 6 and 9 of Broadbalk using two soil pits (20 cm × 20 cm × 20 cm) per plot. Soil samples from the FYM+N3 (Strip 2.1), Nil (Strip 3) and N1+2+1PKMg (Strip 18) plots on sections 1 (standard pesticide regime) and 6 (no fungicide use since 1985) were collected for commercial pesticide analyses. More than 400 compounds (organo-chlorine pesticides, pyrethroids, organophosphorus pesticides, organonitrogen pesticides) were screened by Eurofins Limited. Straw was collected from Broadbalk Section 1. This was screened for 350 pesticides using a standard acidified methanol/water extraction followed by analysis by liquid chromatography with mass spectrometric detection (HPLC-MS/MS) by FERA Limited. Observations and results were tweeted using '@wormscience'. Invitations were accepted to disseminate the results at local farmers' events.

2.4 | #30minworms farmland earthworm survey (Autumn 2018)

To address issues in such surveys identified previously (Stroud, 2019), a website was established (www.wormsurvey.org) for the research project that provided free open access to an earthworm identification tutorial, YouTube demonstrations, a downloadable method booklet and a link to the online form for entering results and survey feedback. Farmers were tasked to assess five soil pits per field (20 cm × 20 cm × 20 cm size, hand-sorted), counting and classifying earthworms into the ecological group. By uploading their results, informed consent was given but no personal (identifying) information was requested or recorded (i.e. the survey was anonymous). Survey feedback was in response to questions spanning: previous experience in earthworms, the role of earthworm monitoring in soil health, the usefulness of the earthworm tutorial, the hardest part of the method and how long it took to complete. In terms of the earthworm results, an interpretation was scored as a 'pass or fail', where failure meant there was no evidence of either the widespread earthworms (found in at least four of five soil pits) or that all three ecological types of worms were present. There was no press release. The survey (September–November 2018) was advertised through Twitter (@wormscience, with 2000 followers), BBC Farming Today (listening audience, >1 million), national general farming press: Farmers Weekly (circulation >53, 000), and the soil specific farming press, *viz*. Direct Driller.

Concomitantly, a single field experiment was intensively sampled at the Rothamsted Broom's Barn Experimental Farm, Suffolk, (52.2605°N, 0.5656 °E, 70 m altitude), which has a temperate climate. The soil is a sandy loam of the Barrow Series. The 7.8 ha field trial has three rotations; a 3-year 'economic', 5-year 'agronomic' and 8-year 'environmental' rotation, and the experiment is arranged as a factorial, randomized block design with each element of the rotation present in every year of the experiment in duplicate. Full details can be found elsewhere (e-RA, 2018). Earthworms were surveyed at the edge of the plots to avoid the central yield strip from being damaged by soil disturbance and trampling. The soil sampling method was identical to the #30minworms survey, a spade was used to dig a 20 cm × 20 cm × 20 cm soil pit etc but at a high sampling intensity. Two earthworm sample pits per plot (n = 126 measurements in one 7.8 ha field) and the mean earthworm population (abundance, ecological group, biomass) was determined. During sampling, observations were tweeted using @wormscience and #30minworms to make visible participation in the farmland earthworm survey more visible. Engagement between people included retweets, comments and likes. Invitations were accepted to discuss the results at farmer's meetings around the country.

2.5 | #WorldWormWeek farmland earthworm survey (Spring 2019)

'#WorldWormWeek' ran between 23–31 March 2019 and was disseminated using social media (Twitter, @wormscience, 2500 followers). The use of the hashtag and video views were noted. Feedback informed the design of the online results portal (agrantec.com). This facilitated the sharing of an optional image of the earthworms, and an image analysis sheet (scale bars and colour wheel) was provided with the downloadable method booklet. Through uploading results including basic field management, informed consent was again provided. The data were used to populate a spreadsheet, and the online entry portal had the capacity to provide instant feedback to all the participants. The results dashboard included the participants individual results and summary graphs of the real-time earthworm data including numbers of earthworms and results entries submitted.

We surveyed 66 field units at Rothamsted farm during #WorldWormWeek and added this data to the online results portal. The 330 ha Rothamsted Research Farm (51.82 N and 0.37 W), Harpenden, UK has a temperate climate in the Midlands of England (regional climate). The soil is characterised as a flinty silty clay loam of the Batcombe series. During sampling, observations were tweeted using @wormscience, questions were answered using 1-min videos and engagement with people included retweets, comments and likes. Project funding ended shortly after the survey, so all invitations to discuss the results had to be declined.

2.6 | Review of #WorldWormWeek by a number of researchers

On 4 April 2019, the farmland earthworm survey had at least 50 entries (indicating collaboration). The first author emailed 30 researchers with details of the research project, a summary of the results (including images), and the link to a Google form which contained voluntary questions asking for their opinions on the survey's fitness for use, with space for specific comments. Through participation, informed consent was provided. The review was open for 1 week and the data used to populate a spreadsheet for analysis.

2.7 | Statistical analyses

Genstat (18^{th} eddition, VSN International Ltd., UK) was used to perform the statistical analyses. The data means were assessed using *t*-tests, with differences obtained at levels $p \leq 0.05$ were reported as significant.

3 | Results

3.1 | Farmland earthworm survey (Autumn 2017)

The informal researcher-farmer surveys covered 16 fields under ploughed, minimum tillage and no-tillage cultivation. However, these categories are subjective: operator, equipment used, and soil moisture influence cultivation intensity, such as by the number of passes and cultivation depth. Epigeic earthworms were found in seven fields, endogeic earthworms in all 16 fields, and anecic earthworms (or their middens) in 13 fields (SI Table 1). That is, tillage-sensitive, straw feeding earthworms were detected in 54–81% fields. Informal conversations during sampling indicated that farmers had a perception of earthworms in terms of numbers but not ecological groups. Farmers qualitatively monitored earthworm presence through observing bird numbers during tillage. Reducing tillage, specifically to conservation tillage practices (straw retainment, shallow non-inversion tillage) were thought to improve water infiltration and so reduce ponding in patches of fields, attributed to earthworm activities. There was interest in comparing earthworm survey results with those from Broadbalk, questions about the impact, if any, of pesticides on earthworms and the benefits of novel tillage equipment, such as a cross-slot drill (recently purchased by a local farmer). On Broadbalk earthworms were dominated by juveniles and were widespread (92% presence in soil pits). In terms of adult earthworm presence, the 144 soil pits yielded no epigeic earthworms, 44% of pits contained endogeic earthworms and 7% of pits contained anecic earthworm(s) (SI Fig. 1). Middens were widespread on the FYM and FYM+N3 treatment strips. Four fungicides were detected in soil samples, with epoxiconazole detected at the highest concentrations (0.13–0.26 mg kg^{-1}) (SI Table 2). The organochlorine insecticide Aldrin/Dieldrin (which is not currently used on Broadbalk but had been in the past) was detected, with concentrations 4× higher in the FYM plot compared to the Nil plot. Broadbalk straw was screened for 350 pesticides and five fungicides were detected (SI Table 3). The highest concentration detected was epoxiconazole at 0.4 mg kg^{-1}.

3.2 | #30minworms (Autumn 2018)

There were 152 results entries equivalent to 760 pit assessments. The participants reported a range of previous earthworm survey experience, with 13% of participants never monitoring their earthworms, 30% informally monitoring and 55% were previous participants who had experience formally identifying and recording their earthworms (Fig 1a). The majority (94%) of participants thought that earthworm monitoring was likely to improve soil health (Fig 1b). The earthworm identification quiz was shared with the previous #60minworms participants for beta testing, resulting in requests to improve the photo quality before uploading to the website. In terms of its usefulness, 91% of the #30minworms participants used it and said it was helpful (Fig 1c). There were also two written comments in the feedback section: "quiz really helpful". In terms of the hardest part of the method, 5% of the participants provided no response, 2% reported it was "all easy", 18% choosing which field to sample, 1% midden identification, 15% physically digging the soil pits and 59% earthworm identification

(Fig. 1d). In terms of the time taken, the majority (91%) of participants reported the survey took <60 mins (Fig. 1e).

A total of four, 647 earthworms were independently assessed over 1628 hectares, meaning a sampling intensity of one sample per 2.1 hectares. A total of 52% fields were reported to have all three ecological groups, and the widespread presence of earthworms. Of the fields which did not meet this criteria: in 34% fields no epigeic earthworms were found, in 16% fields no endogeic earthworms were found and in 19% no anecic earthworms (or middens/signs of them were found), whilst in 22% fields earthworms were not widespread (present in ≤ 3 of the 5 soil pits). In terms of tillage, 26% of conventionally tilled (ploughed), 50% of MinTilled and 61% of No-Tilled fields recorded ecological group diversity and the widespread presence of earthworms (Fig. 2).

The research experiment at Brooms Barn received no rainfall for fifty days between June – July 2018, a prolonged drought. The field average Autumn earthworm population was 36 ± 5 earthworms m^2 ($n = 126$). That is 1.4 earthworms per 20 cm × 20 cm × 20 cm soil pit. No epigeic earthworms were found, recorded species included the endogeic *A. chlorotica* (pale and green), *A. caliginosa*, and *A. rosea* and endo-anecic *A. longa* and the anecic *L.terrestris*. Earthworms were not widespread (only 61% soil pits contained an earthworm). Therefore within-field management comparisons were not possible.

Invitations to farmer events enabled informal conversations about reasons for non-participation, including not knowing about the survey, or meaning to participate but forgetting (e.g. sampling booklet later found in car glovebox or under other paperwork). Learning outcomes included problems with crop residue degradation (absence of litter feeding earthworm types), the discovery of compaction issues resulting from biosolids spreading (and decision to cease amendments because of soil structure damage by contractors), and a decision to sell a field (which was thought to be a poor field) for the development into a car park (fewest earthworms in the Tyne catchment survey).

3.2.1 | #WorldWormWeek (Spring 2019)

There was much interest in earthworms, for example, the 'How to sample' demonstration was viewed 6779 times. The #WorldWormWeek hashtag was independently disseminated by groups with large followings including BBC Spring Watch, Woodland Trust, Natural England, Soil Association, Buglife, AHDB and DefraSoils, with a total social media audience of ca. 1 million people (SI Figure 2). The interest in #WorldWormWeek resulted in the European Journal of Soil Science launching an online special issue making selected earthworm research papers open-access (EJSS, 2019). There were 18 entries from other countries including Australia, New Zealand, China, Bangladesh, India, Nigeria, Uruguay and the USA, i.e. from every continent except Antarctica. As the timing was not idea for some regions, email updates were provided about earthworm populations later in the year e.g. from Nigeria. Data cleaning to remove partially completed entries resulted in 247 fields in the UK (every climate region), spanning over 2200 hectares with 11464 earthworms assessed. Results were submitted from 'other' field management, pasture/ley and wilderness (woodland/scrub). A total of 54% of fields were reported to have all three ecological groups, and the widespread presence of earthworms. Of the fields which did not, 38% fields recorded no epigeic earthworms, 8% fields no endogeic earthworms and 22% no anecic earthworms (or middens/signs of them were found), whilst in 9% of fields earthworms were not widespread (present in ≤3 of the 5 soil pits). In terms of tillage, 33% of conventionally tilled (ploughed), 44% of MinTilled and 76% of NoTilled fields reported ecological group diversity and the widespread presence of earthworms (Fig. 3). Photographic evidence was optional and uploaded with 22% of entries. These were of mixed quality, with common issues being blurry, pixelated, too dark, muddy earthworms or only selected earthworms photographed, all of which inhibited result verification. A total of 6% of the entries could be verified by the high quality images submitted.

3.2.2 | Review of #WorldWormWeek by a number of researchers

The review had an engagement rate of 40% (12 of the 30 invited researchers participated). Two invited researchers got in contact after the survey ended because they had been away and indicated they would like to contribute (but anonymity would be lost therefore the survey was not re-opened). Respondents had previously participated in on-farm events and had an interest in earthworms, and 75% read the information provided about the survey prior to answering the questionnaire.

Four data scenarios were presented for evaluation and feedback. The majority response (46%) was a slight confidence in the data quality. Without images to verify earthworm results 9–36% researchers were “not at all confident” in the data, but with images to verify the data this issue was resolved. If the image and data matched, the rating “confident and very confident” was 72%; however, if they did not match, requiring the data to be moderated, this rating declined to 45%. The majority (54.5%) said that images were essential, where 45.5% people thought they were useful, but not essential, and no one thought images were inappropriate for this type of survey.

The majority of researchers would recommend the survey to farmers and policy makers and rated it as likely to improve soil health in agriculture (Fig 4). There was a universal agreement that long term monitoring was needed (100%), with other popular developments suggested being integrating the data with soil parameters (92%) and with field management records (67%). Perceptions of usefulness revealed that the survey was most useful to the general public and rural community, and least useful to scientists and policy makers (Fig 4). The critical knowledge gap is the patchiness of earthworm populations within fields (SI Table 4).

4 | Discussion

4.1 | Evaluation of the hypotheses

Hypothesis (1) was supported. There was a 100% positive response to the direct approach of on-farm surveys in Autumn 2017, the indirect approach in Autumn 2018 resulted in farmers generating independent earthworm population 'scores' for their fields (152 entries) and Spring 2019 resulted in participation from people around the World. This may seem like a low threshold of support for the hypothesis, but although the UK OPAL earthworm survey spanned 2856 sites – only 16 were from arable fields: farmer engagement cannot be assumed (Archer *et al.*, 2009). Globally, the BioBio project in Europe concluded there was a need to mobilise farmers to sample their own fields for earthworms (Targetti *et al.*, 2014), with a similar need for participation was reported in South Africa, requiring tailored methods and identification support (Nxele *et al.*, 2015). Farmers' ecological knowledge is not considered to be a research priority in developed countries (Pauli *et al.*, 2016), yet the use of soil health tests is linked to how well the biological and physical results align with farmers' knowledge and experience (O'Neill *et al.*, 2021).

The #30minworms survey attracted people who had never monitored earthworms, those who informally monitored earthworms on their farms and returning participants. They all shared the idea soil health can likely be improved by earthworm monitoring (Fig. 2). Almost all the participants improved their knowledge of earthworm ecological groups using the tutorial and devoted 30 – 60 minutes to soil monitoring (Fig. 2), despite 1 in 7 participants recording it was physically demanding (Fig 2).

Hypothesis (2) was also supported. The surveys culminated in farmers using the standardised method and uploading their results to the online results portal, with results from the research sites collected and uploaded to the portal at the same time. That is, there was effective collaboration between communities that was publicly visible (SI Figure 2). This is important because the majority (86%) of participating farmers were interested in comparing their earthworm data to that from research experiments to support their decision making (Stroud, 2019).

In terms of learning outcomes, it is difficult to satisfy all end users (farmers and researchers) and customers of research (grant funders) when visual, verbal and digital communication is the preference of farmers, but written approaches (especially refereed publications) are the communication style expected from the scientific community (Aare *et al.*, 2020). For example, local farmers asked questions about earthworms and pesticide levels on Broadbalk, the long-term arable field experiment at Rothamsted. These questions could not be answered because research into the fate and behaviour of pesticides on Broadbalk was discontinued some time ago (Parliament, 2006), neither earthworm nor pesticide data are routinely collected, and publishing new results from experiments established before statistics informed experimental design in refereed publications is very difficult. Prioritising farmers information needs over publishable outcomes, earthworm and pesticide data was collected in 2017 from Broadbalk and disseminated at farm meetings (SI Figs and Tables). This was timely because the previous absence of information about earthworms and pesticides has been exploited to undermine trust between scientists and farmers (co-producers) using open access data from Broadbalk (Stroud, 2018).

The communication style preferred by participants was verbal and email, resulting in an online data portal to share and compare results. This created a function for co-producers to associate their data with their groups, according to geographical location (Tyne Rivers Trust, Anglian

Water, FWAG, AHDB monitor farmers) or concept (Yield Enhancement Network) with a follow-up meeting to discuss the results and interpretations. The effectively and popularity of this is shown in the high number of invitations to the first author to meetings. Common questions were the impact, if any, of pesticides, flooding/drought and flatworm invasions on earthworm populations. Learning outcomes indicated earthworm sampling delivered much more than the 'score' and interpreting results as 'pass/fail' was wrong for two principal reasons. First, participation is personal and some co-producers were alarmed by a 'fail' rating. This prompted discussion and negotiation about what the results meant and a change to a heuristics presentation style (Fig 3) with interpretation support available on the web portal (SI Fig. 3) which is authentic about uncertainty. Second, the researcher review indicated that the patchiness of earthworm populations at field scales creates unacceptable degrees of uncertainty for rigorous quantification in terms of 'pass/fail'.

In terms of data quality, farmers rated themselves as confident in the data they were collecting but identified a need for earthworm identification support (Stroud, 2019). Hence the online earthworm tutorial was created, and 92% of farmers used it and said was useful (Fig 1). None the less, the majority (59%) of the participants reported the hardest part of the method was earthworm identification, indicating that even more support is needed. The success rate of visual ecological group identification was earlier found to be 88% (Archer *et al.*, 2009), suggesting a 1 in 12 error should be expected. The majority of researchers were 'slightly confident' in the data quality generated by farmers, which increased to 'confident' if supporting images were provided. There is, therefore, considerable potential for future image analysis to improve scientific confidence in data quality. Images were uploaded by farmers for 20% of entries, and around ca.25% of these were of sufficient quality to be used for verification purposes. Moving towards photographic based recording would likely help to resolve issues around identification.

The research scientists contribution to the Autumn 2017 surveys was field sampling with farmers and the survey of pesticides and earthworms on Broadbalk. An epigeic earthworm has never been detected on the Broadbalk Experiment, although this reflects the results of only 4 surveys since 1922. Their absence is unexplained, but it, and overall earthworm community structure may be the result of tillage as Broadbalk has been ploughed for 175 years and is thought to have been in cultivation for at least 400 years. The pesticide concentrations in the samples from Broadbalk were consistent with a survey of pesticide residues in soils across Europe: mixtures of up to 6 pesticide residues in soils are common, most frequently including the fungicides epoxiconazole, boscalid and tebuconazole, at concentrations <0.5 mg kg^{-1} (Silva *et al.*, 2019). The research contribution for the Autumn 2018 survey comprised only one field. Originally, the intensive sampling of the experiment at Brooms's Barn was thought to be sufficient because of the diversity of within-field soil management at the site under factorial, randomized block design (i.e. peer acceptable design). However, there were no epigeic earthworms detected (n = 126 soil pits), earthworms were not widespread (39% soil pits lacked a single earthworm) and the field had a low abundance of just 1 earthworm per (20 cm × 20 cm × 20 cm) soil pit. The population collapse highlights a vulnerability of earthworms to drought, resulting in patches of soil without any earthworms and indicating the need for long-term monitoring. The research contribution in Spring 2019 was the whole of Rothamsted farm, with data being uploaded directly into the online results portal to contribute to the social learning network.

A unique feature of these co-ordinated surveys was strategic timing – measuring earthworms, soil ecosystem engineers, at a time when crops are growing. The results indicate that most no-tillage fields had earthworms which were both widespread (found in at least four out of five soil pits across the field) and included all the three ecological groups of earthworms - in contrast to ploughed fields (Figs 2, 4). This does not mean that earthworms are locally extinct in ploughed fields (the result of digging only five soil pits per field assessment); but indicates that patchy earthworm distributions are linked to habitat disturbance (tillage) in arable systems. Earthworms were not widespread in 9–22% of all fields surveyed, suggesting a limited spatial influence (i.e. the absence of earthworms in multiple patches of a field) is not uncommon. Epigeic earthworms were not detected in 34–38% fields. Epigeic earthworms are tillage sensitive, and the most sensitive of the ecological groups to drought (Edwards & Bohlen, 1996) and are the most sensitive to parasitic infections in pesticide-treated soils (Pizl, 1985). The lack of detection could be patchy distribution patterns associated with a dependence on surface litter conditions, tillage, environmental (earthworms losing too much water to survive a drought) or related to annelid disease (reducing resilience to environmental stresses); the latter is unknown because earthworms die and rapidly decay in their burrows creating a survivorship bias. Endogeic earthworms were not detected in 8–16% of fields – noting earthworms were present in these fields, but only immature earthworms were recorded. This may be a cause for concern because immature earthworms are not yet capable of reproduction. Anecic earthworms were detected both by physical presence and by checking for their semi-permanent middens on the soil surface. Counting middens was preferred to the laborious application of vermifuge to small soil pits, because middens can cover up to 25% of the soil surface (Subler *et al.*, 1998), with abundances ranging from 0–3 middens per m^2 under conventional tillage and up to 28 middens per m^2 under no-till (Simonsen *et al.*, 2010). Research has shown that the abundance of middens is positively correlated to soil health parameters because anecic earthworms stimulate soil biology and engineer soil physical properties (aeration and drainage) (Jemison et al., 2019). It is therefore significant that 19–22% fields had no evidence for anecic earthworms, or signs of them (middens) in both 2018 and 2019. The pilot Spring 2018 survey reported that anecic earthworms were uncommon in one in five fields (Stroud, 2019). Anecic earthworms are least sensitive to drought (Edwards & Bohlen, 1996) and the 2018 survey at Broom's Barn was after a long drought, but found an abundance of both *A. longa* and *L. terrestris* earthworms in the autumn. Their absences are commonly attributed to intensive tillage (Briones & Schmidt, 2017), and they are vulnerable to castrating parasites in soils exposed to air pollution or pesticides (Stroud, 2021).

Hypothesis (3), that researchers would be interested in influencing the survey design to make it meaningful to soil science, was supported. Researchers cautioned potential confounding factors (soil moisture and temperature, earthworm spatial distribution with fields), and knowledge gaps, including the concern that not enough is known about earthworms to be used as an indicator were helpful. However, these cautions did not prevent the survey being considered a credible and legitimate source of information (Figure 4), an issue which often confounds citizen science (Irwin, 2018). Key developments include: verification of data through photographs, long-term monitoring and integration of surveys with soil properties.

4.2 | Considerations for future approaches

Over the past 25 years, two models have emerged for structuring information systems to aid decision making processes (Gigerenzer & Gaissmaier, 2011; Harrison *et al.*, 2011). For decades, soil science has been shaped towards the optimisation model (Baveye *et al.*, 2016), in which scientific attention is directed towards making a universal knowledge claim e.g. earthworm abundance benchmarking (Phillips *et al.*, 2019). The approach involves distant, statistical analysis and classification to create mechanically elegant models of controlled, artificial situations. The alternative ecologically rational standpoint was explored here, that land management is a knowledge-based system dependent on expert behaviours. Thus, researcher attention is directed towards collaboration and amplifying peer-to-peer learning through digital tools. This approach is a type of social innovation known as ‘successor science’ in human-computing interaction fields (Harrison *et al.*, 2011). In agriculture, researchers have explored farmers attitudes to soil degradation and soil health which indicated direct finance was unpopular, with a preference for facilitating farmer-to-farmer learning, using co-productive or participatory approaches (Wheeler & Lobley, 2021). A diversity of decision strategies rather than the 'one size fits all' may fit within the policy concepts of a sustainable society, e.g. the UN Sustainable Development Goals and the EU 'Green Deal'.

Citizens excel at measuring visual properties and the activities of earthworms, first recognised by Charles Darwin (Darwin, 1882), and here digital connections co-ordinated earthworm measurements at unprecedented geographic scales to the ecological group level. The frequently asked questions highlighted key scientific research gaps in the fate and behaviour of pesticides. This is particularly relevant to earthworms because the consumption of earthworms by vertebrates can result in the trophic transfer of pollutants, and spread of fatal parasitic diseases to wildlife and farmed animals (Stroud, 2021). Hence why earthworm monitoring based on numbers is ineffective and the post-registration monitoring of pesticides is essential.

Research funding ended in 2019 bringing our science-farming partnership in earthworm monitoring to an end. None the less it is being used widely. For example, the method has been adopted for the ASDA (supermarket), NIAB and University of Cambridge soil health testing guidelines (NIAB, 2020). It is being independently trialled as a metric for the soil structure target for the Department of Environment, Farming, and Rural Affairs by the Environment Agency, Sustainable Soils Alliance and Centre for Ecology and Hydrology (SSA, 2021). It is also being independently trialled for the Global Farm Metric, with investment by banks, major UK supermarkets, policy makers in England and Wales, environmental NGOs and the National Farmers Union (SFT, 2021).

5 | Conclusion

This project was based on the hypothesis that science-farming partnerships are essential to understanding how our behaviours can sustain or enhance the life-sustaining components of the soil ecosystems that we are dependent upon. It demonstrated that there is an appetite for civic science projects in the farming community, and that there are widespread and unexplained absences of anecic earthworms. Most surveyed researchers thought than an earthworm survey would likely improve farmland soil health and would recommend it to farmers and policy makers. The survey is being independently taken forward and used as a metric by both private and public stakeholders, demonstrating authentic knowledge transfer in soil science.

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FIGURE LEGENDS

Fig. 1. #30minworms participant responses.

Fig. 2. #30minworms (Autumn 2018).

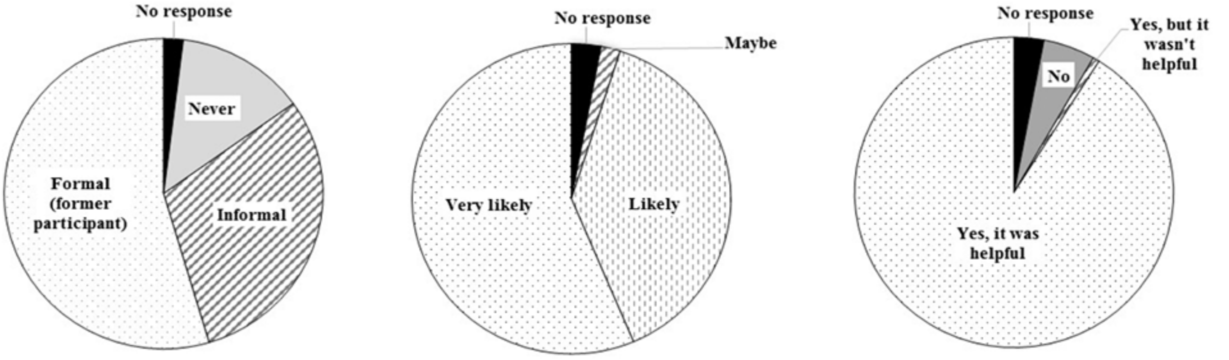
Fig. 3. #WorldWormWeek (Spring 2019). The results portal was designed for arable systems - but participants uploaded ‘other’ arable, pasture/ley and wilderness.

Fig. 4. Researcher responses to the earthworm survey.

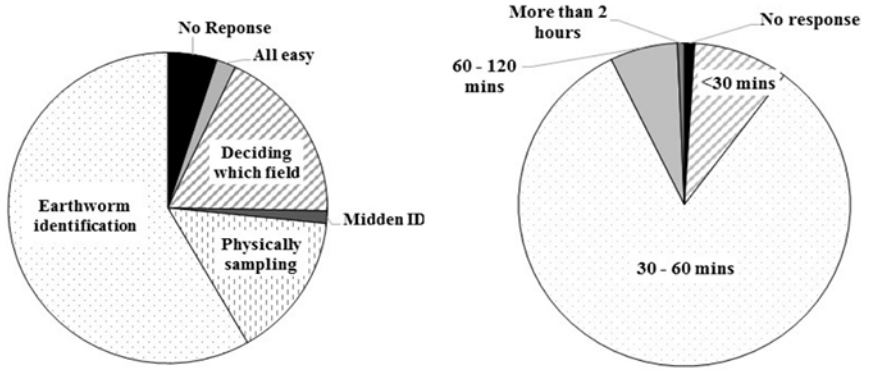
Si Fig. 1: Average earthworm numbers in 17 plots across 4 sections of the Broadbalk Wheat Experiment showing earthworm abundance. Data are mean ± SE.

SI Fig 2: Examples of Twitter interactions.

SI Fig. 3: Decision aid using earthworm community structure information.



(a) Earthworm survey experience? (b) Earthworm surveys improve soil health? (c) Did you use the tutorial and was it helpful?



(d) Hardest part of the method? (e) How long did the field survey take?

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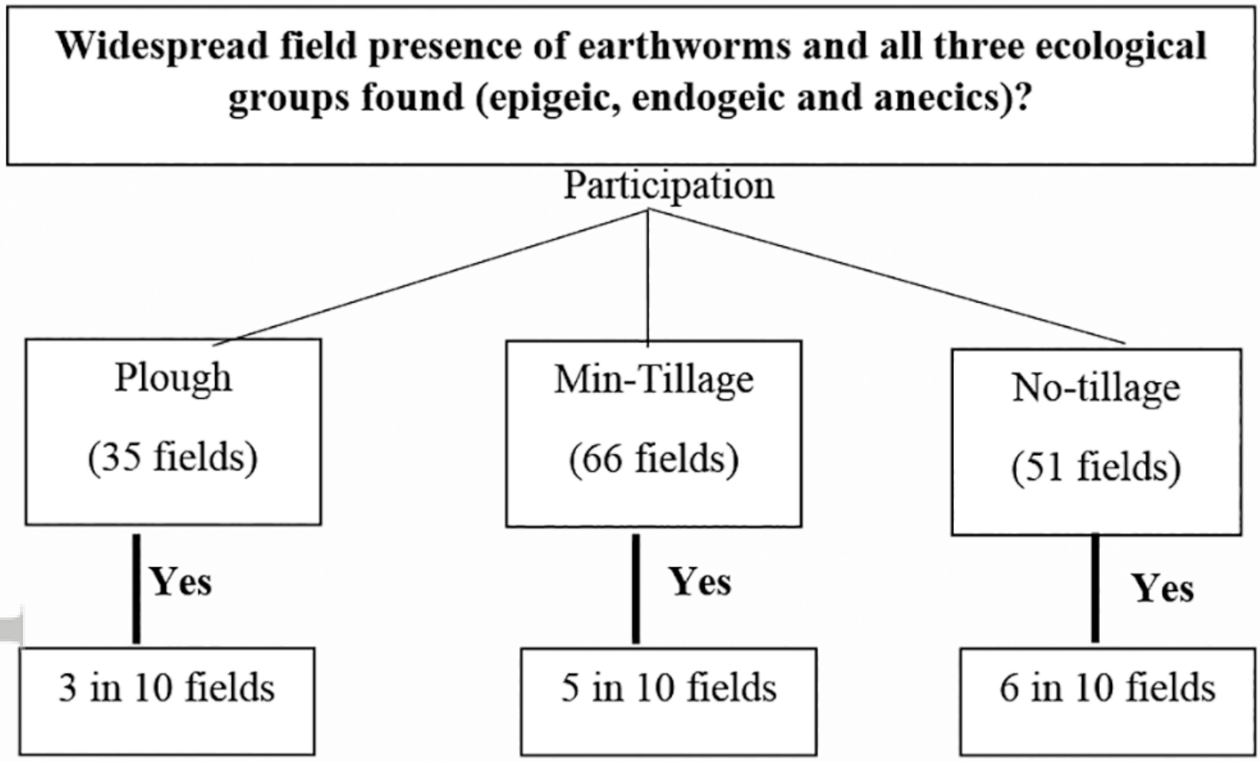

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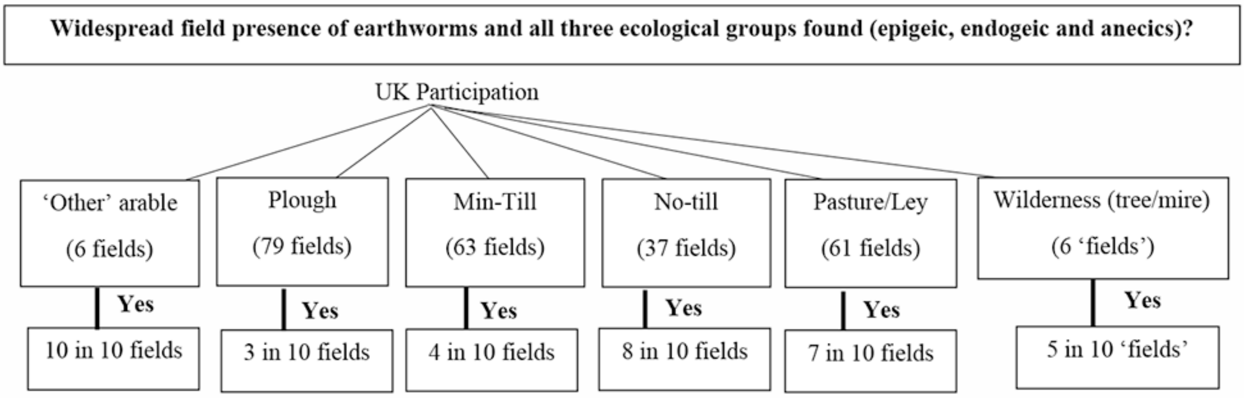

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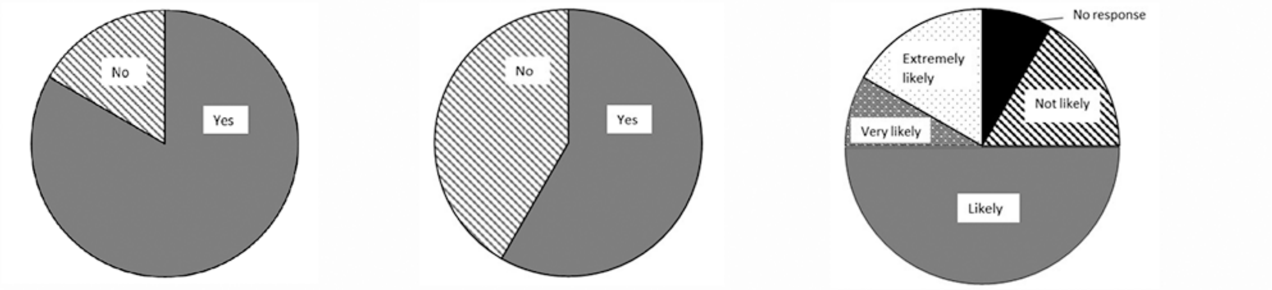
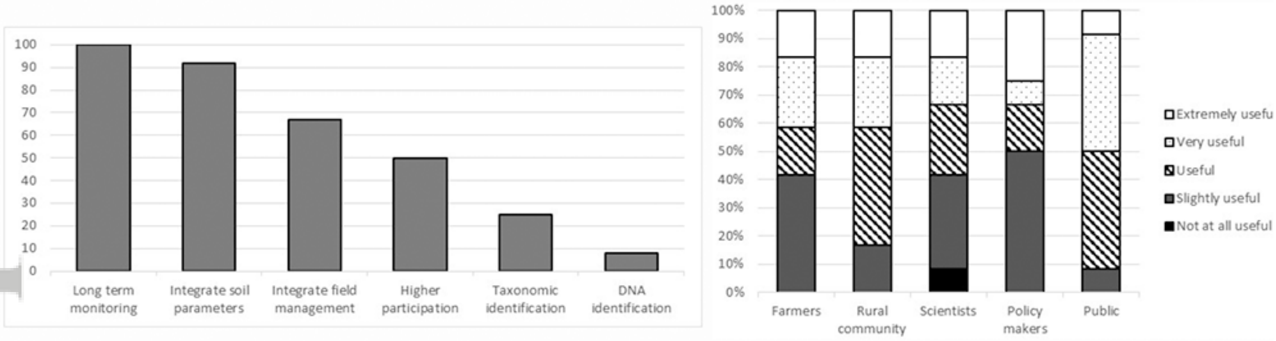


(c) Recommend survey to farmers?

(b) Recommend survey to policy makers?

(a) Earthworm surveying improve soil health?



(d) Popular developments for the earthworm survey

(e) Perceptions of usefulness to different groups

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