

1 **Soil health pilot study in England: outcomes from an on-**
2 **farm earthworm survey**

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4 **Short title: Farmland earthworm survey**

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25 **Abstract**

26 Earthworms are primary candidates for national soil health monitoring as they are ecosystem
27 engineers that benefit both food production and ecosystem services associated with soil
28 security. Supporting farmers to monitor soil health could help to achieve the policy aspiration
29 of sustainable soils by 2030 in England; however, little is known about how to overcome
30 participation barriers, appropriate methodologies (practical, cost-effective, usefulness) or
31 training needs. This paper presents the results from a pilot #60minworms study which
32 mobilised farmers to assess over >1300 ha farmland soils in spring 2018. The results
33 interpretation framework is based on the presence of earthworms from each of the three
34 ecological groups at each observation (20cm³ pit) and spatially across a field (10 soil pits).
35 Results showed that most fields have basic earthworm biodiversity, but 42 % fields may be at
36 risk of over-cultivation as indicated by absence/rarity of epigeic and/or anecic earthworms; and
37 earthworm counting is not a reliable indicator of earthworm biodiversity. Tillage had a
38 negative impact ($p < 0.05$) on earthworm populations and organic matter management did not
39 mitigate tillage impacts. In terms of farmer participation, Twitter and Farmers Weekly
40 magazine were highly effective channels for recruitment. Direct feedback from participants
41 included excellent scores in trust, value and satisfaction of the protocol (e.g. 100 % would do
42 the test again) and 57 % would use their worm survey results to change their soil management
43 practices. A key training need in terms of earthworm identification skills was reported. The
44 trade-off between data quality, participation rates and fieldwork costs suggests there is potential
45 to streamline the protocol further to #30minuteworms (5 pits), incurring farmer fieldwork costs
46 of approximately £1.48 ha⁻¹. At national scales, £14 million pounds across 4.7 M ha⁻¹ in
47 fieldwork costs per survey could be saved by farmer participation.

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49 **Introduction**

50 There is now a significant interest in sustainable soil management and policy in England to
51 achieve the Department of Farming and Rural Affairs (DEFRA) aspiration of sustainable soils
52 by 2030. A sustainable arable agricultural system is considered to have both sustainable crop
53 production for food security and a ‘healthy’ soil for soil security. However, there have been
54 few soil surveys to inform both land managers and policy makers about the state of farmland
55 soil health in England to best support evidence-based decision making.

56 Over the past decade there have been a number of successful public soil surveys in England
57 using earthworm populations including the Open Air Laboratories Soil and Earthworm Survey
58 which included 0.4 % sites in arable fields[1]; the Natural England earthworm surveys which
59 included 1.8 % sites in arable fields[2]; and a school citizen science invertebrate survey (0 %
60 sites in arable fields)[3]. Although earthworms are a primary candidate (out of 183 potential
61 biological indicators) for national soil health monitoring[4], there has been limited farmer
62 participation to date. Mobilising farmers to monitor soil health could be an effective way to
63 improve the national sustainability of soil management. For example, the ‘monitoring effect’
64 where farms taking part in monitoring activities improve their biodiversity faster than farms
65 not taking part in monitoring[5], fits well with sustainable soil policy aspirations for UK
66 agriculture.

67 Arable soils typically contain 150 – 350 earthworms per m² and high populations (>400
68 earthworms per m²) are linked to significant benefits in plant productivity, including cash crops
69 such as wheat [6]. There are three ecological functional groups: epigeic earthworms break
70 down surface crop residues and their presence is linked to the breeding season success rates of
71 the song thrush (*Turdus philomelos*), the latter whose populations have rapidly declined in
72 England[7]. Anecic earthworms incorporate surface organic matter into the soil; and support

73 water drainage for plant production[8] and deep crop rooting[9]. UK endogeic earthworm
74 species mix organic and mineral components together to form stable aggregates which benefit
75 spring crop emergence and carbon sequestration[10]. In this way, earthworms support both
76 food production, but also wider ecosystem services associated with soil security. There is no
77 evidence that earthworm biodiversity is constrained in the UK[11], and invasive flatworms
78 which are earthworm predators are largely geographically restricted to Western Scotland and
79 Ireland[12]. Thus, arable soil management is a key factor controlling the relative abundance of
80 these ecological functional groups.

81 In terms of arable soil management, both epigeic and anecic earthworm species are highly
82 vulnerable to conventional tillage[13], meaning earthworm community structures could be
83 used to indicate over-cultivated soils. Crop establishment practices have been dominated by
84 this intensive mechanical cultivation for decades[14], and this continues to be the principal soil
85 management practice for establishing arable crops in England [15]. It is well known that tillage
86 has an adverse effect on the environmental services provided by soils [16]. Over-cultivation
87 impacts soil biological, physical and chemical properties, for example, causing a decline in
88 surface-feeding earthworms to local extinction levels[13, 17], reduces water stable aggregation
89 which increases the risk of erosion and nutrient losses, and may decrease soil organic carbon
90 levels with implications for climate change[18]. It is unclear as to the extent organic matter
91 management can mitigate the effects of tillage, as the impact of these management activities is
92 subject to local conditions[17].

93 To date, the use of earthworms in national monitoring schemes has been held back by the
94 absence of a standardised methodology [4]. For example, all three ecological earthworm
95 surveys in England over the past decade have used a different methodology [1-3]. These
96 methods differ from the ISO 23611-1 earthworm assessment method which includes formalin
97 as a vermifuge, precluding its application in citizen science projects. A limitation of the largest

98 international survey of farmland earthworm populations (EU FP7 BioBio) was the skilled
99 labour based protocol and high labour cost (on average 4.8 person days (£3 k) per farm for
100 earthworm fieldwork alone, not including taxonomic identification)[5].

101 The ultimate aim of monitoring is to cost-effectively convey robust information to those who
102 are expected to use it [19]; essentially the trade-off between data quality, practicability, cost
103 and usefulness. The principal cost of monitoring is labour; for which the UK has the highest
104 person day costs in the EU [5]. Research from the EU FP7 BioBio project indicated significant
105 cost reductions (46 %) could be achieved if farmers could be mobilised to assess their own
106 farms; however, key research areas include how to overcome participation barriers; the
107 development of protocols that require lower technical expertise; identification of training needs
108 and quantifying sampling bias [5]. To date, one small study assessed the usefulness of
109 ‘earthworms’ (numbers and species) for farmland biodiversity assessments to administrators,
110 farmers and consumer groups, with earthworms ranked 5th (out of 6 parameters) by all groups
111 [19].

112 The aim of the #60minworms pilot study was to support farmers to monitor their own field(s)
113 and generate results that are useful to their soil management decisions. A number of gaps in
114 on-farm earthworm monitoring are addressed, and the state of farmland soils in England as
115 indicated by earthworm populations under different monitoring and interpretation scenarios are
116 presented.

117 **Methods**

118 The #60minworms pilot study (100 fields target) ran between the 15th March – 30th April 2018
119 (Fig. 1). There was no need for ethical approval as this was undertaken by volunteers (farmers)
120 on their privately-owned land (farms). Survey booklets were distributed directly (at soil health
121 workshops in March) or following a request and posted to potential participants in order to

122 quantify recruitment and participation channels. All the participants received a report on their
123 earthworm populations and were invited to take part in the Rothamsted #60minworms workshop
124 on the 3rd May 2018. The workshop was based around a ClikPad audience response system to
125 quantify sampling design bias, method compliance, competence, usefulness and future
126 developments, and afterwards, an earthworm identification class was held (at participants
127 request). The outcomes were adopted to make the new Agricultural and Horticultural
128 Development Board (AHDB) factsheets ‘How to count worms’ freely available as printable
129 leaflets in June 2018, with an initial print run of 2000 copies, distributed at agricultural events
130 such as Cereals (leading technical event for the arable industry with up to 20,000 visitors) and
131 AHDB strategic and monitor farm events (24 sites around the UK) (Supplementary Information
132 (SI) booklet).

133 **Fig. 1:** *Recruitment, participation and engagement in the #60minworms survey. The key*
134 *mobilisation routes were through Twitter and Farmers Weekly, the survey attracted participants*
135 *with no earthworm monitoring experience and the primary feedback preference was a*
136 *workshop.*

137 The #60minworms methodology was designed around the presence of earthworms in the field,
138 enabling a rapid traffic-light based interpretation. The participants required five pieces of
139 equipment to perform the survey: a garden fork to dig the soil pit, a ruler (as 20 cm size pits
140 needed), a mat (to put the soil on for hand-sorting *in-situ*), a pot with a lid (to stop earthworms
141 escaping) plus a small volume of water (so the earthworms do not dry out) and the results booklet
142 (including a simple earthworm key) with a pen. A timer was recommended to complete the
143 hand-sorting within 5 minutes, unless the soil was too wet or compacted to sort efficiently and
144 time was increased to 10 minutes. Thus, the equipment and consumable costs were negligible;
145 and, an experienced sampler could generally complete the survey in 60 minutes. The procedure
146 was to dig a 20 cm x 20 cm x 20 soil pit and place the soil on the mat. The soil is hand-sorted,

147 placing each earthworm into the pot. Once the soil has been sorted, the total number of
148 earthworms were counted and recorded. The earthworms were separated into adults (for further
149 analysis) and juveniles (returned to the pit). Adult earthworms were separated into an ecological
150 functional group (epigeic, endogeic or anecic) using a simple key. There are high levels of
151 cryptic diversity within UK earthworm species[22], thus species level assessments are beyond
152 the scope of this agricultural soil health assessment. The total numbers of epigeic (small red
153 worms), endogeic (pale or green worms) or anecic (heavily pigmented, large worms) adults were
154 recorded for each pit. After analysis, the adult earthworms were returned to the pit. This was
155 repeated 10 times via a W-style sampling pattern across the cropped field.

156 To address some of the common concerns relating to earthworm analyses, the seasonal
157 reproducibility was tested on nine AHDB strategic farm fields (eight arable and one grass field)
158 in October 2017 and April 2018. To assess the reliability of 10 or fewer soil pits per field; 20
159 soil pits per field (n = 9 fields) were measured. To assess the accuracy of hand-sorting
160 earthworms in 5 minutes, sorted soil was re-sorted for 5 minutes and earthworms were collected
161 for further analyses. This was performed by three volunteers on nine fields (range of soil
162 textures and crop types) (n = 27 pit resorted) in April 2018. To indicate year-on-year
163 variability, previous scientific field trial based earthworm surveys[23] (using the identical soil
164 pit size and hand sorting methods), with at least two years of data were re-analysed (to remove
165 vermifuge data and categorise the species into their ecological groupings), and recalculated on
166 a per pit basis using the likelihood formula.

167 Instant results analysis is possible in five categories: (a) widespread presence, (b) epigeic, (c)
168 endogeic, (d) anecic presence, and (e) presence of earthworm ‘hotspots’ of earthworms via a
169 simple likelihood formula:

$$170 \text{ Likelihood} = \left(\frac{a, b, c, d \text{ or } e}{p} \right) \times 100$$

171 Total number of pits (p) where at least:

172 (a) one earthworm was found (juveniles or any adults below),

173 (b) one adult epigeic earthworm was found,

174 (c) one adult endogeic earthworm was found,

175 (d) one adult anecic earthworm was found,

176 (e) high numbers (≥ 16 earthworms per pit, ≥ 400 earthworms per m^2) of

177 earthworms (total number including all juveniles and adults) found

178 The traffic light system interpretation indicates a red, ‘unlikely’ category (<33 %), the amber,

179 ‘possible’ category (>33 – 66 %) and the green ‘likely’ category (> 66%), and is reported on a

180 field basis (Table 1).

% Occurrence	Likelihood:
0 – 1	Exceptionally unlikely
1 – 10	Very unlikely
10 – 33	Unlikely
33 – 66	As likely as unlikely
66 – 90	Likely
90 - 99	Very likely
99 - 100	Almost certain

181 **Table 1:** *The interpretation framework is based on the presence of earthworms for each*

182 *observation (one soil pit) across a field (10 soil pits).*

183 The satisfactory threshold was the possible $\geq 40\%$ score for each category, providing evidence

184 for basic earthworm biodiversity in-field; where the likely >66 % score provided good evidence

185 for basic earthworm biodiversity. Scores $\leq 10\%$ for presence and/or an ecological group are
186 sub-optimal, as there is little evidence for spatial impacts (widespread presence of an earthworm
187 ecological group to support plant productivity and wider ecosystem services); and temporal
188 impacts (an adults' lifespan is in the order of years, and given reproduction capacity increases
189 the likelihood of that ecological function being sustained in the future). Earthworm numbers
190 were not of primary interest because the interpretation is dependent on fertiliser usage, soil type,
191 crop type etc[6]. but to calculate the average number of earthworms per hectare the following
192 formula was used:

193 (f) *Earthworms per hectare* = (mean number of earthworms per pit $\times 25$) $\times 10000$

194 Whilst the results (simple percentages) could be calculated by the participants, they were
195 requested to either post or email a copy of their findings, and include basic field management
196 details including field name, size, postcode, crop, tillage (notill, minimum tillage and ploughed),
197 and Yes/No answers to organic matter management: residue retained, cover cropping and
198 whether an organic waste e.g. compost had been used this year, in order to inform on general
199 soil management practices and earthworm results. A total of 10 participants with either depleted
200 or exceptional earthworm results were contacted and visited.

201 Following the submission of all the data, Genstat (18.2.0.18409, 18th addition, VSN
202 International Ltd., UK) was used to perform one-way ANOVAs to assess trends in earthworm
203 populations and soil management practices. Labour cost estimates were calculated using a £:€
204 exchange rate of 1.12; in order to translate private agency skilled worker (€89.75 h⁻¹) and farmer
205 (€28.39 h⁻¹) [5]. To calculate costs at farm, regional and national scales, DEFRA official
206 statistics (February 2018) were used [24]. The survey data was compared against the earthworm
207 soil health thresholds proposed in this paper; and the proposed AHDB soil health scorecard
208 earthworm number thresholds[25] to estimate the state of farmland soil health.

209 **Results**

210 **Recruitment and engagement of farmers**

211 Participants recruited through Twitter had exceptional recruitment and engagement rates of up
212 to 55 %, and engagement was amplified to ‘96 %’ (multiple fields surveyed) by participants
213 recruited through Farmers Weekly (Fig. 1). In contrast, no engagement (0 %) from potential
214 participants recruited via the soil health workshops or newsletters was found. The Rothamsted
215 #60minworms workshop was attended by participants from a diverse range of management
216 practices, primarily interested in improving soil health assessments and no prior experience in
217 earthworm monitoring (Fig. 1).

218 **Cost and usefulness of the #60minworms survey**

219 Most participants (77 %) reported spending 5-mins hand-sorting each soil pit, enabling
220 completion within 60 minutes. The number of samples was fixed at 10 replicates, but field
221 surveys ranged between 2 to 80 hectares (average observation was 1.08 ± 0.08 pit per hectare)
222 and the longest reported survey took 3 hours. Using the person (farmer) day costs in the UK[5],
223 where the majority (66 %) of participants performed the #60minworms analysis alone means
224 the typical farm labour costs were €28 (£25). A total of 34 % participants completed the survey
225 with fieldwork support provided by up to 3 people, increasing the cost to €84 (£75) per field.
226 The real farm labour costs (in-kind) for the 126 field #60minworm pilot field study can
227 therefore be estimated to be in the order of €5928 (£5300); which on a per hectare basis is €4.50
228 (£4).

229 There were a range of motivations for taking part in the #60minworms survey, and excellent
230 scores in value, trust and satisfaction of the method (Fig. 2); for example, 100 % of the
231 participants would do the #60minworms survey again. There were very high scores for

232 community science in every category; where 100 % participants would recommend the survey
233 to others, 93 % of participants rated other participants' competence was very important and 87
234 % participants would use of scientific field trials to aid their interpretations; which corroborated
235 with the high (29 %) primary use of results would be to compare their results to others (Fig. 2).
236 Further, most participants would use the survey to compare soil management practices on-farm
237 (36 %); which is in agreement with participants performing multiple field surveys and change
238 their soil management practices based as a result earthworm monitoring results (57 %
239 participants) (Fig. 2). There was no interest in regional trends, with usefulness only linked to
240 relevant comparisons and threshold values (Fig. 2).

241 **Fig. 2:** *Usefulness of the #60minworms survey to farmers. Feedback included trust, value and*
242 *satisfaction in the protocol by participants (100 % would do the test again) and an extremely*
243 *high interest (>85 %) in community science (including other participants and scientists) with*
244 *a key use in comparing results*

245 **Quality control and application**

246 There was full geographic coverage in England and a range of management practices surveyed
247 (Fig. 3). Choosing the smallest field was not a sampling strategy by any participant, and good
248 levels of compliance were recorded, for example, all participants measured the size of their soil
249 pit(s). A key training need in earthworm identification skills (Fig. 3). Farmers reported a
250 problem capturing deep burrowing *Lumbricus terrestris* anecic earthworms which could be
251 solved by amending the method to include a tick box for the presence of middens/characteristic
252 large vertical burrows. There are three common anecic earthworm species in England
253 (*L.terrestris*, *A.longa* and *A. nocturna*), and middens are a good indicator of *L.terrestris*[26-
254 32], the earthworm most sensitive to conventional tillage [13].

255 **Fig. 3:** #60minworms survey participation. There was a broad geographic spread over
256 England and a range of field management practices. There was little indication of bias in
257 sampling strategy, problems in compliance or results quality, but there was a key training need
258 in terms of earthworm identification skills.

259 The intensive sampling at the AHDB strategic farm fields also measured the accuracy of 5-
260 minute soil pit handsorting for earthworms. Resorting soil for a further 5-minutes led to an
261 additional 1.6 ± 0.17 earthworms per pit per field (regardless of earthworm population size),
262 ranging in biomass from 0.05 – 0.429 g per earthworm, of which 91 % were juveniles; meaning
263 the underestimation of 40 worms per m^2 (or 400, 000 ha^{-1}) on each field. The variability of
264 earthworm populations over annual scales was high for earthworm numbers (SI, Table S1); but
265 the presence (or absence) of each ecological group was consistent (SI, Table S1, S2).
266 Comparing results at 20, 10 and 5 sampling pits per field; 10 sampling pits would incur an error
267 of 16 % in categorizing the earthworm groups; of which 4 % would be a false negative (i.e. 0
268 %, no sightings on that ecological group which is uncommon rather than absent); five sampling
269 pits per field would incur an error of 33% in categorizing the earthworm groups, of which 15
270 % would be a false negative.

271 **#60minworms survey results**

272 Earthworm counts within a 10-pit field survey ranged by 6.4-fold, from a minimum 1.3 to a
273 maximum difference of 28-fold. The average earthworm field population was 2.4 ± 0.4 million
274 worms ha^{-1} and ranged by 100-fold, between 0.75 to 7.3 million worms ha^{-1} . The field
275 characteristics of the top and lowest 10 populations of earthworms shared soil textures, tillage
276 and field management practices (SI, Table S3). Tillage significantly ($p < 0.05$) impacted the
277 general earthworm presence, epigeic presence, anecic presence, presence of hotspots and
278 number of earthworms per hectare (SI Fig. S1, Table S4). Organic matter management included

279 straw retention, cover cropping or manuring (including animal manures, compost, anaerobic
280 digestate, humic substances or biosolids). The only significant impact on the numbers of
281 earthworms was straw retention ($p = 0.04$), Table S4. Cover cropping, significantly impacted
282 the presence of anecic earthworms ($p = 0.03$), (SI Fig. S2, Table S4).

283 A total of 77 % fields had a 100 % presence of earthworms (at least 1 earthworm per pit), with
284 the lowest presence recorded at 30 % for one field. There were no sightings of epigeic
285 earthworm on 21 % fields, and anecic earthworms on 16 % fields (Table S5a), with a further 8
286 – 11 % fields have rare sightings of these groups (10 % presence). There was a good (≥ 67 %
287 presence) of endogeic earthworms on most fields (Table S5a); and a good presence of all three
288 ecological groups together on 15 % fields. Earthworm hotspots (≥ 16 earthworms per pit) were
289 uncommon; 46 % fields had no earthworm hotspots, where a good presence of hotspots was
290 detected on 13 % fields. Overall, 42 % fields had sub-optimal earthworm populations, defined
291 as ≤ 10 % presence for at least one ecological group, providing little evidence for the spatial
292 and temporal presence of epigeic, endogeic and/or anecic earthworms.

293 **Trade-offs between data quality, participation rates and cost**

294 The aim of #60minworms was to indicate soils at risk of over-cultivation through the
295 absence/rarity of epigeic and anecic earthworms that have well known sensitivity to tillage.
296 Reducing the sampling intensity to five soil pits (e.g. #30minworms) and changing the sub-
297 optimal threshold to < 20 %, shows good agreement to the 10-pit survey ≤ 10 % category
298 threshold (Tables S5b, c). An alternative metric is to rate the soil health of a field based on
299 earthworm numbers at a sampling intensity of one soil pit per field as proposed for the AHDB
300 soil scorecard[25]. This survey indicates that between 68 – 88 % fields could be categorized
301 as ‘depleted’ through to ‘active’ (Table S6). In comparison a sampling intensity of five soil
302 pits per field provided average earthworm count data that was in good agreement with these

303 data calculated at 10 soil pits per field (Table S6), and 20 % of fields would be categorized as
304 ‘depleted’ at this sampling intensity. However, even at a high soil pit replication ($n = 10$) there
305 was a limited concomitant relationship between #60minworms ecological group absence(s) and
306 AHDB soil scorecard ‘depleted’ earthworm numbers in field classifications (Table 2). For
307 example, no adult earthworms were found on six fields; but 33 % of those fields were classified
308 as ‘active’ as earthworm number thresholds are weighted towards juvenile earthworm
309 abundances.

310 The trade-off was estimated using data quality (% false negatives), participation (scaling
311 booklet requests to 100 % and actual survey time to 100 %) and cost (using an intensive 20 pits
312 x 10 minutes earthworm fieldwork set at 100 %), indicates that a five-pit field survey has
313 significant potential (Fig. 4). An average #30minworms field survey ($10.9 \pm 0.8 \text{ ha}^{-1}$) would
314 incur £16 – 48 in fieldwork costs depending on labour type (farmer or outsourced). Scaling to
315 #30minworms of the whole arable area (52 %) of an average farm in England (85 ha) would
316 range between £65 – 196 in fieldwork costs depending on labour type. Significant regional
317 variations in farm costs would be expected; fieldwork costs on the arable area on an average
318 farm in the North East being £23 - 70, where the East of England would cost £134 – 401;
319 reflecting farm size and arable cropping area. Nationally, a #30minworms survey of the entire
320 4.74 million hectares of land under arable cropping would have fieldwork costs at £7 million
321 (farmer participation) to £21 million (outsourced) per survey.

322 **Fig. 4:** Trade-offs between earthworm fieldwork effort (30 – 240 mins) and data quality,
323 farmer participation levels and labour costs.

324 **Table 2:** Fields interpreted as ‘depleted’ differ between the interpretation method, noting that the proposed AHDB numbers scorecard analysis
 325 is based on the mean of 10 soil pits (*not one pit as proposed for this method). A total of 42 % fields may have over-cultivation issues (no
 326 evidence of ecological group presence); where as ‘depleted’ earthworm numbers occurred on 20 % fields; these indicators do not necessarily co-
 327 occur.

328

#60minworms interpretations			AHDB earthworm numbers scorecard*			
<i>≤10 % ecological group presence</i>			<i>Fields categorized by mean earthworm counts per pit (n = 10 soil pits*)</i>			
(i.e. rare/absent)	Fields (n)	Notes	<4 (depleted)	4 – 8 (intermediate)	>8 (active)	‘Depleted’ fields agreement (%)
3 ecological groups	6	Depleted	3	1	2	50 %
2 ecological groups	16	Depleted	12	4	0	75 %
1 ecological group	31	Depleted	4	12	15	13 %
<i>≥10 % ecological presence</i>	73		6	20	47	92 %
Fields depleted (%)	42 %		20 %			48 %

329

330 **Discussion**

331 The pilot #60minworms study effectively mobilised farmers to reach the target of 100 fields
332 (Fig. 1). It was hypothesised that the workshops and newsletters would lead to the highest
333 recruitment and participation rates due to a direct interaction and targeted approach (requiring
334 a high time and cost), but posed a risk of location bias i.e. small geographic area monitoring.
335 However, these channels had no impact on participation. Twitter, Farmers Weekly and The
336 Farmers Forum were the most effective channels for recruitment. Twitter and Farmers Weekly
337 recruits had exceptional participation and engagement rates, demonstrating the potential
338 importance of these media channels to achieving soil security in agriculture. A high interest in
339 community science was identified at the #60minworms workshop, with participants placing
340 high value on others' results, data collection abilities and motivations for sampling (Fig. 2),
341 which would likely explain the impact of e.g. Twitter and Farmers Weekly over that of the
342 isolated workshops and newsletters; with a further benefit of the wide geographic survey spread
343 (Fig. 3). The community concept is further corroborated by the primary application of
344 monitoring being to compare results within and between farms (64 %), and a high (87 %)
345 interest in annual earthworm results from scientific national capability field trials e.g.
346 Broadbalk indicating the potential to amplify both spatial and temporal soil health monitoring
347 over and above what is achievable by these groups individually. Future developments that
348 prioritize quick assessment protocols to enhance participation rates (farmers and number of
349 fields), such as a #30minworms survey (Fig. 4) would likely be the most useful to farmers, as
350 most participants (57 %) would change their soil management practices as a result earthworm
351 monitoring results. This is in agreement with the 'monitoring effect', which is a confounding
352 factor for gauging biodiversity[5], but is aligned with the DEFRA aspiration of sustainable
353 soils by 2030. The absence of interest in regional data agrees with the primary interest in soil

354 management (Fig. 2), and may explain the low participation rates by farmers in ecological
355 earthworm surveys to date. At a national scale, £14 million pounds per #30minworms survey
356 could be saved by mobilising farmers; demonstrating the potential high value of farmer input
357 to achieving sustainable farmland soil policy.

358 The #60minworms method is a protocol validated for farmer applications, with feedback
359 indicating high levels of trust, value and satisfaction by the participants (Figs 2, 3). There
360 were no indications of significant sampling bias or problems in method compliance, however
361 a key training need in earthworm identification skills was identified e.g. 46 % participants
362 were not confident in their earthworm adult/juvenile separation and identification skills, but a
363 significant interest in gaining this skill (Fig. 1). Farmer feedback led to modifications and
364 improvement to the methodology and results presentation (SI booklets).

365 The findings from the #60minworm survey showed that earthworms are ubiquitous in UK
366 farmland, with 100 % presence recorded on the majority (77 %) fields. The majority of these
367 fields are managed under conventional agriculture (i.e. pesticides and inorganic fertilisers are
368 used), and intensive cultivations have dominated crop establishment practices in England[15].
369 There was a significant ($p < 0.05$) impact of tillage on all parameters except endogeic
370 earthworm presence (SI Fig. S1, Table S4). The survey revealed that there were no sightings
371 of epigeic and anecic earthworm species, which are the two most sensitive ecological groups
372 to tillage[13], on 21 % and 16 % fields respectively, and they were rare (≤ 10 % presence) on a
373 further 8 % and 11 % fields (SI Table S5a-c). This is a cause for concern given the slow
374 earthworm population recovery rates under changed management practices [33], and slow
375 anecic earthworm reproduction rates, for example 8 cocoons per earthworm per year, with a 60
376 week development time [34]. No earthworm hotspots were detected in almost half (46 %) fields,
377 where ≥ 16 worms per pit are linked to significant benefits in plant productivity
378 (although this is highly dependent on a number of factors so does not have a strong

379 interpretative value)[6]. At these measured on-farm population levels, these data indicate the
380 majority of UK farmland soils have satisfactory earthworm biodiversity, but there is potential
381 to increase the presence of these ecosystem engineers to better support both food security, but
382 also wider earthworm-mediated ecosystem services such as native wildlife prey, soil
383 aggregation and water infiltration; associated with soil security.

384 The aim of #60minworms was to indicate farmland soils at risk of over-cultivation through the
385 absence/rarity of epigeic and anecic earthworms that have well known sensitivity to tillage.
386 Here the ‘traffic light’ for results interpretation here was ranked as useful (36 %), but has an
387 escalating error in categorizing earthworms at ≤ 10 sample pits, which could hinder
388 participation whilst increase costs of monitoring (Fig. 4). Simplification is needed for a
389 #30minworms survey, for example simply a ‘sub-optimal’ or ‘satisfactory’ score, the former
390 indicated by < 20 % (b) epigeic, (c) endogeic and (d) anecic earthworm (or midden/vertical
391 burrow) presence), would mitigate the problem of ‘false-negatives’ as both absent and rare
392 (≤ 10 % presence) are within this ‘sub-optimal’ category (SI Table S5b,c). To aid the
393 identification of exceptional earthworm populations for case-studies of soil management
394 practices; Gold (100 %), Silver (≥ 80 %) and Bronze (≥ 60 %) ecological group presence could
395 be used; of which 15 % of fields in this survey would have achieved a Gold or Silver rating.
396 An alternative metric is the proposed soil health scorecard, using an identical size soil pit and
397 hand-sorting, but at a sampling intensity of one pit per field and earthworm thresholds derived
398 from Brazilian cropping systems [25]. In terms of quality control, there is a high labour cost
399 (doubling of the hand-sorting assessment to 10-minutes for accuracy to improve the detection
400 of juvenile worms), although a correction factor of 1.6 worms pit⁻¹ could be used; the analysis
401 may require five soil pits to provide a robust earthworm number estimate (SI Table S6) and
402 this is a parameter with high annual variability (Table S1). The interpretation of ‘earthworm
403 numbers’ is unclear, for example, earthworm numbers are linked to benefits in plant

404 productivity, but this impact depends on soil texture, crop type and fertilisation regime [6],
405 confounding the interpretative power of this parameter. A total of 20 % fields were identified
406 as ‘depleted’ in earthworm numbers (Table 2), as this metric is primarily influenced by juvenile
407 and endogeic earthworm abundance. In comparison, 42 % fields were depleted in adult
408 ecological groups (principally epigeic and anecic earthworms with known vulnerability to
409 tillage; good sources of food for native wildlife and roles in litter cycling and water drainage).
410 This would explain why there is a limited concomitant relationship between the detection of
411 ‘depleted’ fields using these interpretation schemes (Table 2). This could impact the
412 ‘usefulness’ of earthworm data to farmers when interpretations of their fields significantly
413 differ between scientists.

414 General strategies to increase the presence of earthworms would be to reduce tillage frequency
415 and intensity (SI Fig. S1), however the impact of soil management activities is subject to local
416 conditions (SI Table S3), and monitoring is an essential component to realising soil health in
417 practice. One strategy that provides little benefit to earthworm populations is organic matter
418 management (SI Fig. S2, Table S4). Three types of organic matter management were recorded,
419 with straw retention or manuring having no significant ($p > 0.05$) impact on the presence of
420 the ecological groups. However, cover cropping significantly ($p < 0.05$) increased the presence
421 of anecic earthworms only (SI Fig. S2, Table S4). There was little evidence for organic matter
422 management mitigating tillage impacts on earthworm populations. Identifying ‘at risk’ fields
423 (up to 42 % fields in this survey), through the absence/rarity of epigeic and anecic earthworms,
424 provides, for the first time, the opportunity for management intervention strategies to mitigate
425 the effects of over-cultivation and support the DEFRA policy aspiration of sustainable soils by
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427

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530

531 **Acknowledgements**

532 I'd like to thank the #60minworms participants for their invaluable inputs.

533

534 **Supporting information**

535 **Supplementary Table S1.** Survey analysis using the hand-sorting data from multiple annual
536 assessments on field trials managed under different organic matter rates and types. Despite
537 large fluctuations in earthworm numbers, there was a consistent community structure.

538 **Supplementary Table S2.** Limited seasonal variation in earthworm community structures
539 was detected on the AHDB Strategic Farm East in Autumn 2017 and Spring 2018 (n = 20 pits
540 per field)

541 **Supplementary Table S3.** Field characteristics of the top and bottom 10 fields in the
542 #60minworms survey.

543 **Supplementary Table S4.** P values from one-way ANOVA analyses of the #60minworms
544 data set showing the significance of tillage on all parameters except endogeic presence. In
545 comparison organic matter management practices of straw retention, cover cropping or
546 manuring had little significant impact on earthworm parameters, with only cover cropping
547 having a significant impact on anecic earthworm presence.

548 **Supplementary Tables S5a-c.** (a) The percentage of fields under earthworm ecological
549 group presence categories, where no sightings are 0 % and may indicate a local extinction;
550 and a likely presence is > 66 %, indicating there is good evidence for their presence based on
551 10 soil pits. (b) Fields with a sub-optimal ≤ 10 % presence (absent, rare) presence of
552 earthworm ecological groups. (c) The percentage of fields under earthworm ecological group
553 presence categories, where no sightings are 0 % and may indicate a local extinction; and a

554 likely presence is > 66 %, indicating there is good evidence for their presence based on 5 soil
555 pits.

556 **Supplementary Tables S6.** The field interpretation of earthworm counts at five pits
557 compared to 10 pits is similar. However, there is high uncertainty at a low sampling intensity
558 (one sample pit per field) as most fields (68 – 86 %) contain at least one pit (out of 10 pits) at
559 each of the earthworm categories. This indicates that there is a considerable risk in over-
560 estimating sub-optimal earthworm populations.

561 **Fig. S1.** The #60minworm survey results showed a negative impact ($p < 0.05^*$) of tillage on
562 earthworm presence (a, b, d, e) and numbers (f) (except endogeic presence).

563 **Fig S2.** The #60minworm survey found no significant ($p > 0.05$) impacts from straw retention
564 or manuring management practices. Cover cropping had no significant ($p > 0.05$) impact on
565 epigeic or endogeic earthworm presence, but a beneficial impact ($p < 0.05^*$) on anecic
566 earthworm presence.

567 **Supporting information S1 Booklet.** #60minworms Pilot study booklet, AHDB ‘How to
568 count worm’ factsheets and new #30minworms booklet

569

Aim: 100 field #60minworms farmer participation Spring 2018

Outline: 300 #60minworms booklets available; 227 #60minworms booklet requests; sent by post to potential participants

Outcomes: 126 fields surveyed; 1318 ha farmland area; 7 surveys was the maximum returned by one participant (complicating engagement calculations)

Participant recruitment channels:

Primary recruitment tweet: 28,401 impressions
@Rothamsted (institute, >10k followers);
@wormscience (scientist, 1.7k followers);
@soil_security (funder, 1k followers).

National farming press article

Farmers Weekly, circulation 59,000 - 'Farmers worm count'
15th March 2018 .

Agricultural Forum

The Farmers Forum, members >32,000 - 'Scientist seeks
volunteers' post

Soil health workshops in March

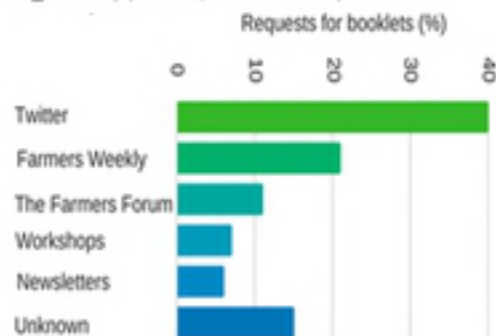
Southern England and Northern England
114 people in total

Newsletters by stakeholders

Unknown circulation

Unknown

Phone calls or email requests without source noted.



Engagement metrics: #60minworms participation

@wormscience

Total: 171,600 impressions; maximum: 23,794 per post; maximum engagement rate: 8.9 %
40 % twitter recruits used #60minworms to post photos of fieldwork and reviews

Participant requests

Modifications to 'traffic-light' shading to hatchings to improve accessibility to colour blind participants (Done)

YouTube method and worm ID demo (Done)

Views: 218; total watched (305 minutes), average view time: 1 min 40 seconds

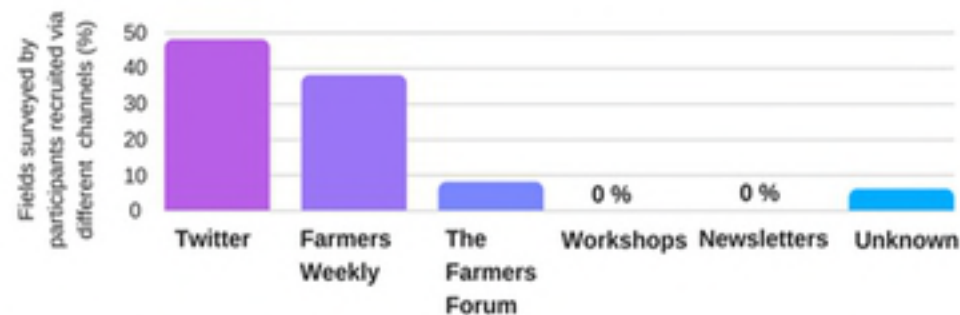
Feedback via workshop and earthworm ID class:

11 % #60minworms participants attended

Top three email and phone questions: When to sample (soil temperature); (2) Suitable for children to participate? (3) Sample specific crop/soil type?

Engagement metrics: recruitment:

Rothamsted #60minworms project page: 733 page views, average page time 3 mins 22 secs
The Farmers Forum: 26 responses, 1134 views, discussion and reviews

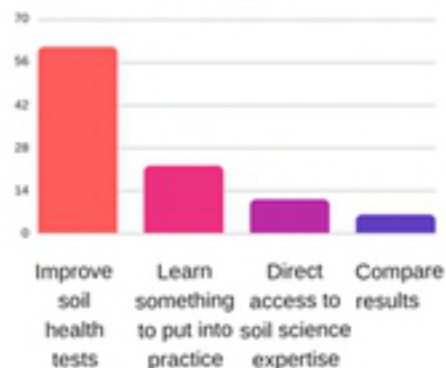


Twitter recruits had an approx. 55 % participation rate (participant booklets returned). Farmers weekly recruits had an approx. 40 % participation rate, but multiple field surveys amplified 'participation' rates to 96 %.

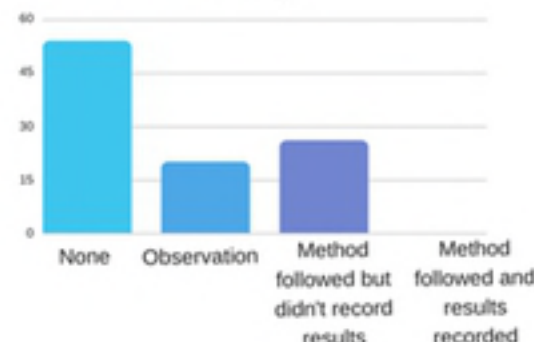
Workshop participants: 56 % rated their knowledge of earthworms as below average

Full spectrum of fields (#2) - (#126), organic, conventional, NoTill, MinTill and Plough based field management
Results: 19 % were pleased, 25 % were as expected, 13 % disappointed and 50 % no idea what to expect

Primary motivation for attending workshop:

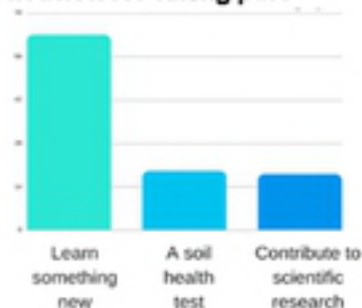


Prior experience of earthworm monitoring:



Usefulness

1. Motivation for taking part



2. Method acceptance and results report

100% participants would recommend the test to others
100% participants would do the test again
100% participants found the results report informative

3. Community soil science

Other people sampling accurately and reproducibly was ranked as very important by 43% and extremely important by 50% participants
100% participants believed others reported their data truthfully
100% participants ranked others data quality as 'medium' on a 3 point scale from high to low
81% participants would like some information about the surveyor e.g. experience (how many surveys), sampling style (e.g. best or worst field) and/or competence in earthworm ID (e.g. a certificate) to aid their interpretations
87% participants would find annual earthworm results from national field trials e.g. Broadbalk, useful to their interpretations

7. Future use of the survey

46% Annual monitoring on-farm
23% Take part in an organised survey event e.g. national scheme
31% Specific soil management on-farm

8. Future developments

87% participants would like to see the method digitised (results entry, open database)

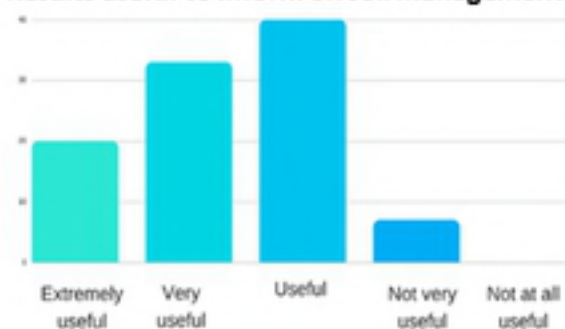
5. Results Impact

57% participants would change their soil management practices as a result of earthworm monitoring
43% participants would take earthworm monitoring into consideration
0% participants had no application for the results

6. Primary use of the results

0% Regional comparisons
36% Comparisons to thresholds
36% Test management practices on-farm
29% Comparing to others results

4. Results useful to inform on soil management practices



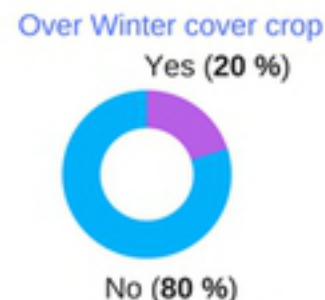
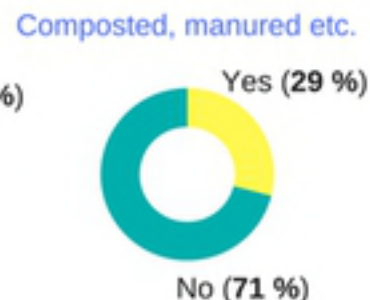
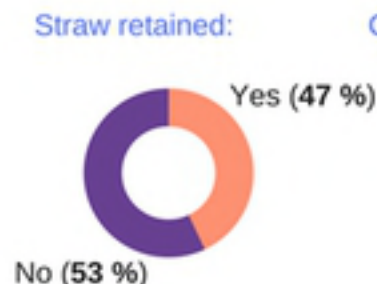
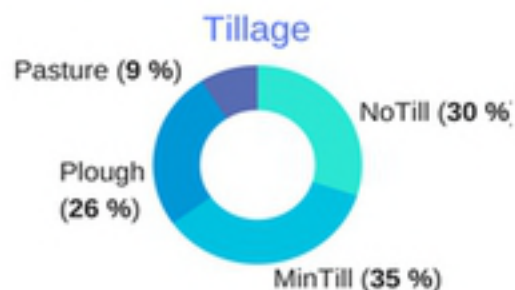
#60minworms participation

Broad geographic range

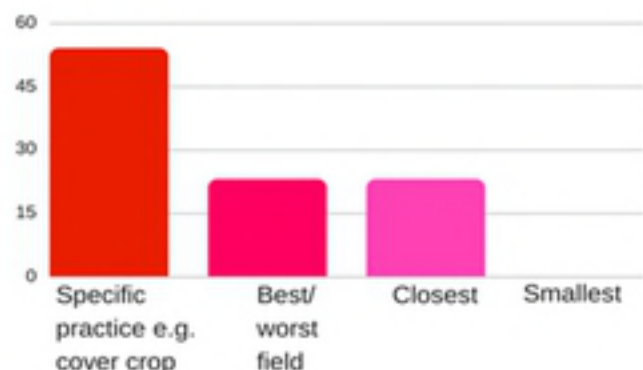
Every region in England (except London)



Field management practices:



Field sampling strategy



Crop type at time of field assessment?

44 % fields in Winter Wheat

Method compliance:

How W was your W (10x soil pits)

31 % W-shape across a field

38 % Known variation across a field

31 % Included tramlines and other interesting spots

Pit size 20cm³?

0 % Measured every soil pit

31 % Measured first few soil pits until 'got eye in'

69 % Measured the spade/fork used for digging

0 % No measurements

5-mins handsorting the soil?

77 % Yes

23 % No

Confidence in data collection:

Handsorting (capturing majority of earthworms)

38 % Extremely confident

46 % Very confident

15 % Confident

0 % Not confident

0 % Not at all confident

Confidence in adult/juvenile separation and earthworm ID?

8 % Extremely confident

23 % Very confident

23 % Confident

46 % Not confident

0 % Not at all confident

Confidence in own data collection quality?

57 % High

43 % Medium

0 % Low

Hardest part of the method?

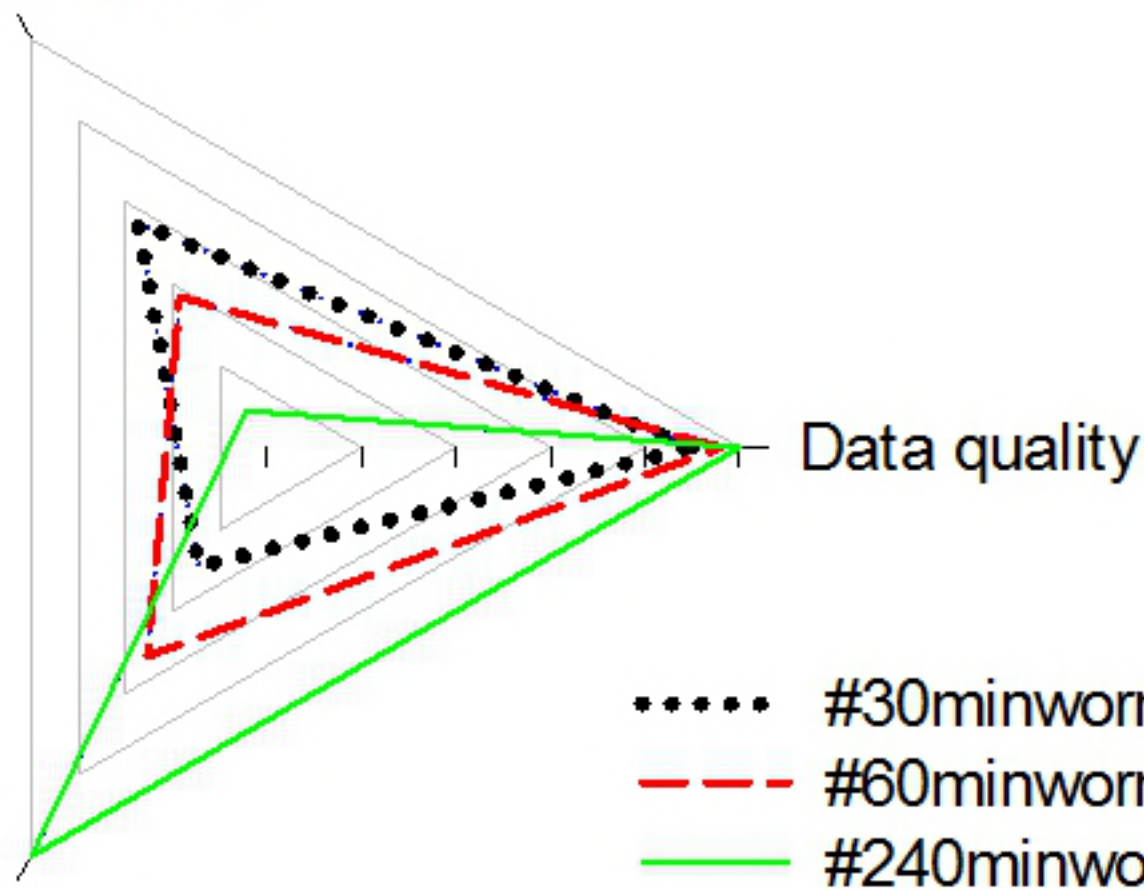
0 % Understanding the instructions

8 % Deciding where to sample

15 % Physically digging the 10x soil pits

77 % Earthworm identification

Farmer participation



Fieldwork labour cost