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ORIGINAL ARTICLE

Monitoring the effects of pesticide pellets to address farmers' concerns on soil fauna, specifically earthworms

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Abstract

Slugs are a major pest in arable agriculture that are typically controlled by using pesticide-impregnated pellets (molluscicides). We received multiple requests from farmers in 2018 for research into the impact of slug pellets on earthworms because they had been told that ferric-based pellets were 'worm-friendly'. We measured soil fauna feeding activities within *Lumbricus terrestris* middens on a replicated field plot experiment comparing the recommended product rates of a metaldehyde (4%) based or ferric phosphate EDDS (3%) based slug pellets. There was a significant decrease in feeding activity in the presence of either type of slug pellet, particularly in the top 25 mm of the soil indicating movement away from the pesticide. This could be explained by the significantly lower abundance (numbers and biomass) of earthworms in the topsoil. Four months after ferric phosphate-based slug pellet application, there was no significant difference between the control and treated plots in earthworm abundance, indicating the effects were temporary. In the laboratory, individual *Lumbricus terrestris* earthworms consumed up to 4 slug pellets over 14 days and no significant differences in biomass were measured. A burrowing fitness assay indicated that earthworms exposed to ferric phosphate-based slug pellets burrowed to a greater depth. This suggests an avoidance behaviour response, which could also explain the field results. A consultation with farmers ($n = 68$) rated this information service as useful and indicated widespread interest in minimizing the effects of pesticides on non-target soil fauna.

KEYWORDS
earthworms, middens, pesticides, slug pellets

1 | INTRODUCTION

Molluscs (predominantly slugs) are a major pest affecting a wide range of commercial crops in moist temperate regions (Barker, 2002), particularly under zero and minimum-tilled soil management practices (Voss et al., 1998). The UK has 42 slug species, with 70% crop damage caused by slugs linked to the field slug *Deroceras reticulatum* (Schley & Bees, 2003). It has been estimated that a lack of effective slug control products could cost up to £43.5 million a year in lost production in oilseed rape and wheat alone (Nichols, 2014). Although there is interest in biological and cultural methods to control slugs, the most widely used control method by farmers is with chemical molluscicides.

Metaldehyde-based formulations were used in 80% slug pellets globally (Castle et al., 2017). In Great Britain, 85% of molluscicides were metaldehyde formulations (135,684 kg active ingredient) on 1.22×10^6 ha of arable crops during 2016 (FERA, 2018). Metaldehyde is an organic compound that is narrowly toxic to slugs via ingestion and acts on the central nervous system, affecting feeding, mucus secretion and mobility (Henderson & Triebskornz, 2002). It can also be toxic with dermal contact because it damages the cells responsible for mucus production. Efficacy can be compromised because the product is water soluble and readily leached away in wet weather when slugs are more active. Currently, the only chemical alternative to metaldehyde is ferric phosphate-based slug pellets. This type of pellet is permitted for use in organic farming. In Great Britain in 2016, approx. 13% of molluscicides were ferric-phosphate formulations spread on 186,208 ha of arable crops (FERA, 2018). Ferric phosphate is insoluble in water, and pesticide formulations include difference chelating agents, for example ethylene diamine tetraacetic acid (EDTA) or ethylene diamine succinic acid (EDDS), which are used to increase the solubility of the iron, and hence toxicity towards the slugs. Chelated ferric phosphate is ingested by slugs and acts on the digestive system, specifically calcium metabolism, causing the slugs to stop feeding and reduces their mobility (Castle et al., 2017).

In 2018, there was an upcoming ban on metaldehyde due to concerns about its impact on water quality. This research was prompted by the last author receiving multiple requests from farmers (by email and at events in 2018) to investigate effects of molluscicides on non-target soil fauna, specifically, earthworms. Farmers had been told that the ferric-phosphate formulation is 'worm-friendly' (in contrast to other molluscicides). There are two laboratory studies at applications higher than field-application rates, which reported that ferric phosphate EDTA-based formulations were reported to be deleterious to earthworms, with responses including reduced surface feeding activity, increased mortality and reduced growth (Edwards et al., 2009; Langan & Shaw, 2006). The same studies reported that metaldehyde-based slug pellets had no effect on activity, growth or mortality on *Lumbricus terrestris* earthworms (Edwards et al., 2009; Langan & Shaw, 2006). There is a field research knowledge gap, which needs to be resolved to meet the concerns of people who use molluscicides.

In terms of field research, the behaviour of native anecic *L. terrestris* earthworms includes surface foraging. This form of earthworm behaviour is an exposure pathway to chemical molluscicides for two reasons. Firstly, foraging of surface materials includes slug pellets, which can be collected by *L. terrestris* at a rate of 3 pellets per hour (Gavin et al., 2012). Secondly, this native earthworm species is common under zero and minimum tilled soil management practices (Briones & Schmidt, 2017), the management practices associated with higher slug pest pressures (Voss et al., 1998). The product of typical surface foraging activities (plant debris and stones) is the construction and maintenance of a midden (5–15 cm diameter), which plugs their permanent vertical burrow. Middens may be constructed to maintain their burrow microclimate, but their inadvertent chemical molluscicide foraging creates a specific exposure pathway to midden-dwelling fauna. Middens, being piles of redistributed plant debris (an important food source for soil fauna) are hotspots of organisms responsible for decomposition processes. Therefore, we targeted middens to monitor soil fauna feeding activities to estimate the effects of slug pellets. Soil fauna feeding activities are used for ecological risk assessments (e.g. ISO 18311:2016). In terms of *L. terrestris* specifically, ingestion of chemical molluscicides could lead to mobility disorders and laboratory burrowing fitness assays are needed to fill this knowledge gap.

In the present study, we hypothesized that (1) field soil fauna feeding activities (measured as the disappearance of bait in the bait-lamina sticks) would be reduced in the presence of slug pellets, (2) laboratory *L. terrestris* burrowing activities (measured as an excavated volume/continuous pore in a packed soil core) would be reduced for earthworms previously exposed to slug pellets and (3) explore whether this experiment met the information needs of different groups of farmers/advisors.

2 | MATERIALS AND METHODS

2.1 | Field site

The research was performed at Rothamsted Research Institute, Harpenden (51.810°N, 0.367°W), which has a temperate climate in the South of England. The experiment is on a silt loam soil belonging to the Batcombe series. The trial was performed on the New Zealand (NZ) field as a 75-plot experiment in a complete randomized block design with 15 replicates per treatment ($n = 75$ plots, 4 m × 9 m). Previous organic matter amendments (2012–2015) had no effect on the population size, biomass or species diversity of earthworms (Stroud et al., 2023; Whitmore et al., 2017). The experiment is managed under conservation agriculture with crops established using a direct disc drill (Weaving GD3000M). Field management timings in relation to experimental procedures can be found in Table S1.

2.2 | Application of slug pellets

TDS Major, a metaldehyde (4%) based slug pellet and Sluxx HP, a ferric phosphate (3%) based slug pellet were compared against a control treatment (untreated with slug pellets). Further information on the field design can be found in Figure S1. Pellets were applied by hand at the recommended dose rate of 7 kg ha^{-1}, but differences in the pellet size meant that there were 60 pellet points per m^2 for ferric phosphate and 43 pellet points per m^2 for metaldehyde.

2.3 | Field soil fauna assessments

Earthworm populations were measured using standard methods of hand-sorting soil pits (20 × 20 × 20 cm) or vermifuge extractions (0.5 m × 0.5 m quadrat) as previously described (Stroud, 2019; Stroud et al., 2016). Assessments were performed before and after the slug pellet applications (Table S1). Soil moisture (<6 cm) was recorded just prior to the assessment using a ML2 Theta probe (Delta-T Devices).

Bait-lamina sticks were obtained from Terra Protecta GmbH, Berlin, Germany. They were deployed at the same time as slug pellet application (Table S1). We inserted each stick directly into a midden (Figure 1). A total of 5 middens per plot were studied (75 plot experiment, equivalent to 375 feeding sticks in total). Soil temperature and moisture was recorded to check the bait-lamina sticks were deployed under appropriate environmental conditions (5–15°C and moisture >20% for invertebrate activity). After 4 weeks, all the sticks were removed from the soil and bait consumption scored. Scoring was performed by one person who used the ISO two-point scale, specifically, one point if more than half of the aperture was empty, otherwise it was recorded as 0.

FIGURE 1 Deployment of feeding sticks into a midden on an experimental plot treated with slug pellets.

2.4 | Meteorological data

Meteorological data (rainfall, soil and air temperatures) were obtained from the Rothamsted met station, which is located approximately 500 m from the experimental site (ERA, 2018).

2.5 | Burrowing fitness of *L. terrestris* earthworms exposed to slug pellets

2.5.1 | Exposure to slug pellets

Firstly, the earthworms were exposed to slug pellets for 14 days. The Rothamsted Prescribed Mix (RPM soil, Petersfield Products, Leicestershire, UK) (Greenslade et al., 2016) was used. The straw-feeding feeding method (Sizmur et al., 2017) was adapted for the exposure period. A 0.6-litre plastic box was filled with 300 g soil (dry weight) and adjusted to a gravimetric moisture content of 30%. Small adult *L. terrestris* (Worms Direct, Essex, UK) with a similar mass (4.37 ± 0.28 g SD) for used for the study. All soil boxes received 1 g ground wheat straw sprinkled on the soil surface (earthworm food to stimulate mass gain) and one *L. terrestris* earthworm. There were five replicates per treatment: Control (no slug pellets); surface application of one TDS Major (metaldehyde), one Sluxx HP (ferric phosphate) pellet, or mixture with one TDS Major (metaldehyde) and one Sluxx HP pellet per box for 1 week. As *L. terrestris* can forage and feed on 3 slug pellets per hour, an additional surface application of five pellets was applied of TDS major (six pellets in total), Sluxx HP (six pellets in total) and five of each type (12 pellets in total) for the following week. The experiment was arranged in a randomized block design in the incubator (15°C in the dark) for 14 days. The soil boxes were destructively sampled to recover pellets (often buried under casts), and the earthworms were rinsed with water and their mass (non-depurated) recorded.

2.5.2 | Burrowing fitness assay

Secondly, a simple burrowing fitness assay was performed. Each pre-exposed earthworm (n = 20) was placed onto the surface of a packed soil core (275 mm soil with an internal diameter of 63 mm), and the soil cores (n = 20) were incubated for 72 h at a constant temperature (18°C). After 72 h of burrowing activity, 100 mL of mustard-water solution (10 g L^{-1}) was poured on the soil surface causing each earthworm to evacuate the soil (with the exception of one core where the earthworm had died). Each living earthworm was rinsed with water, patted dry and mass recorded. Cores were stored upright before the analysis of earthworm burrow structure by X-ray Computed Tomography (CT scanning). Cores were selected at random as only three per treatment could be analysed within the allotted CT scanning time.

2.5.3 | Soil core analysis by CT scanning

Three replicates per treatment were scanned using a GE Phoenix v|tome|x M 240 kV X-ray CT system (GE sensing and Inspection Technologies). Each column was scanned in two parts (top and bottom) to achieve the full soil depth at a resolution of 105 microns. Individual scans acquired 2400 radiograph images using a detector timing of 250 ms, with an X-ray tube energy and current of 180 kV and 140 μA, respectively. Scans were reconstructed using DatosREC software (GE sensing and Inspection Technologies) and then combined to give a single volume using VGStudioMAX v2.2 software (Volume Graphics GmbH). Typical file size for the combined volumes was 5 Gb.

2.5.4 | Image processing

Image processing analysis was performed on the raw grey-scale images using VGStudioMAX software. Each core was aligned to be upright and image was cropped to a depth of 225 mm from the designated soil surface. The designated soil surface was determined as the uppermost image slice at which the observable pores of diameter >1 cm were located due to the burrowing of earthworms (rather than spaces between midden aggregates). The core was subsequently removed using a cylindrical cropping volume. Burrows were identified using the continuous pore tool, were rendered in white to make them more visible and were saved as new objects. The maximum burrow depth was determined using the 'measurement tool' within VGStudioMAX.

2.6 | Farmer consultation

Farmers' requesting information about slug pellets and earthworms had been provoked by advice (from an unknown source) that ferric-based slug pellets were 'worm-friendly'. We conducted a service evaluation, which was designed and conducted solely to define and judge the information service provided from the field and laboratory experiments. The protocols of human ethical research were followed. The slug pellet field and lab experiments were described in 8 slides within an 87-slide presentation, the same presenter (Stroud) and soil health PowerPoint® presentation was used at each event. A nine-question paper survey was handed out during the presentation to people (farmers and advisors) attending farming events in England in February 2019 (SI Survey). The first group (n = 88 people) had a shared interest (attending a soil and environment conference), the second (n = 25) and third group (n = 19) was just a general, local farm meeting. Characterization was not based on farm characteristics but level of influence in slug control decision-making (e.g. sole decision-maker). The design of the survey included Likert-style closed questions. These were based on a strategy to quickly characterize engagement type (negative, passive, promotion) (Seufert, 2014) to obtain and analyse the range from extremely negative scores (detractors) to extremely positive scores (promotors) and compare the consensus between environmental versus general groups. The participants provided informed consent by handing in the survey (SI Survey). Completed surveys were collected at the end of the presentation by the meeting organizer and returned to the presenter.

2.7 | Data analyses

Genstat (18th edition, VSN International Ltd) was used to perform the statistical analyses. For the feeding activity assessment, General ANOVA (Analysis of Variance) was used with the following parameters: Block: *Block/Plot/Horizon*, Treatments = *(treatment/(Slugpellets*N))*Horizon*. The *block* and *plot* parameters refer to the complete randomized block design of the experiment, and *horizon* refers to bait-lamina consumption (upper horizon 0–2.5 cm; middle 2.5–5 cm and lower horizon 5–7.5 cm). The *treatment* is a two-level factor comparing the control (absence) to the presence of slug pellets, slug pellets included each type of slug pellet (methaldehyde or ferric phosphate-based), *N* was the presence/absence of autumn *N* fertilizer application and *horizon* is as described above. The feeding activity data required a logit transformation with an offset of 1 to meet the normality and constant variance assumptions. For the earthworm abundance assessment, a one-way ANOVA was used with the following parameters: Block: *Block*, Treatments = *treatments (control, metaldehyde, ferric phosphate)*. The earthworm abundance data required a square root transformation to meet the normality and constant variance assumptions. Experiment 1—*Block: block*, *Treatments = pellet/pellet types* where *pellet* is a two-factor category comparing the control (absence) to the presence of slug pellets, and pellet types is each type of slug pellet. The data generated by CT scanning was analysed via ANOVA with a factorial treatment structure (Ferric_Phosphate*Metaldehyde*Vertical_Strata) with a square root transformation of the data. The analysis of general earthworm knowledge and survey feedback was analysed by descriptive statistics using Excel. Differences obtained at levels $p \leq .05$ were reported as significant.

3 | RESULTS

3.1 | Soil fauna feeding activity associated with *L. terrestris* middens

The baseline earthworm assessment found no significant differences in earthworm numbers or biomass (Figure S2). There was 67 mm of rain during the 4-week bait-lamina deployment. The average soil temperature was 10.5°C (max 14.8°C and min 6.6°C). There was a decrease ($p < .001$) in feeding activity in *L. terrestris* middens on plots treated with either metaldehyde or ferric phosphate-formulated slug pellets (Figure 2), compared to the control plots (no slug pellets). There was significantly lower feeding activity in the surface horizon (0–25 mm) (Figure 3) compared to the control plots (no slug pellets). There were significantly ($p = .005$) lower numbers of earthworms (Figure 4a) and biomass ($p < .001$) (Figure 4b) on the plots treated with slug pellets compared to control plots (no slug pellets). No confounding environmental variables were detected between experimental plots, the average soil water content was 33.3 (±2.0) $m^3 m^{3-1}$ and soil temperature 10–11°C ($n = 27$ plots). The earthworm species detected included *Lumbricus terrestris*, *Allolobophora chlorotica*—green form, *Aporrectodea caliginosa* and *Aporrectodea rosea*.

Earthworm abundance was measured again at 16-weeks (February) after slug pellet applications, as numbers for a range of species begin to increase after January (Evans & Guild, 1947). No confounding environmental variables were detected between experimental plots and the soil temperature was 3.9–4.9°C, but populations were low (<50 worms per m^2). Using the vermifuge method, there was no significant difference in earthworm numbers ($p = .394$) or biomass ($p = .608$) between the control and ferric phosphate slug pellet-treated plots (Figure S3). In contrast, using the vermifuge method, earthworm numbers were lower ($p = .02$) on the metaldehyde-treated experimental plots, but there was no significant difference in earthworm biomass ($p = .118$) compared to the control (Figure S3). In contrast, using the topsoil earthworm method there was no significant difference in earthworm populations (numbers ($p = 0.51$) or biomass ($p = .799$)) between the control or any of the treatments (Figure S4). The earthworm species detected included *Lumbricus terrestris*, *Allolobophora chlorotica*—green form, *Aporrectodea caliginosa*, *Aporrectodea rosea* and *Lumbricus castaneus*.

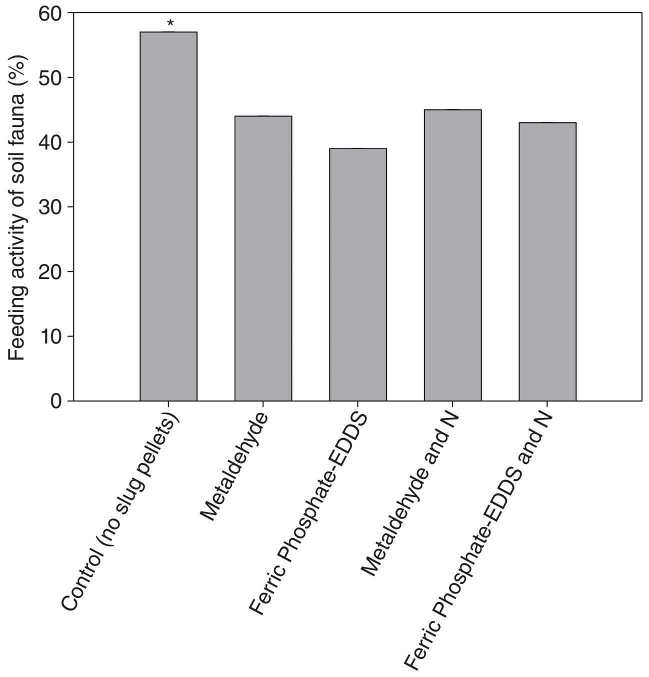

FIGURE 2 Feeding activity by soil fauna (%) in a zero-tillage wheat field trial treatments: no slug pellets ($n = 125$), TDS Major slug pellets (metaldehyde) (n–125), Sluxx HP slug pellets (Ferric Phosphate—EDDS) ($n = 125$), or either of the slug pellets with nitrogen at 30 kg ha^{-1}. There was a significant ($p < .05$) difference between the control and all slug pellet treatments.

3.2 | Burrowing behaviours (laboratory)

Laboratory studies found that there was no significant ($p = .897$) difference in earthworm biomass in the presence of either type of slug pellet (it was estimated each earthworm consumed up to 4 pellets). There was also no significant ($p = .796$) difference in earthworm biomass after the 72-h soil core burrowing activity. There was one earthworm mortality at the burrowing test stage, which suggests this result is an outlier and was treated as such (i.e. not included in the second biomass assessment). Burrowing behaviours were visualized and earthworms demonstrated a range of behaviours including a branching, curved and vertical single burrows and u-shaped (Figure 5). There was no significant difference ($p = .745$) in earthworm burrowing activity (Figure 6a), but there was a significant difference ($p = .01$) in burrowing depth

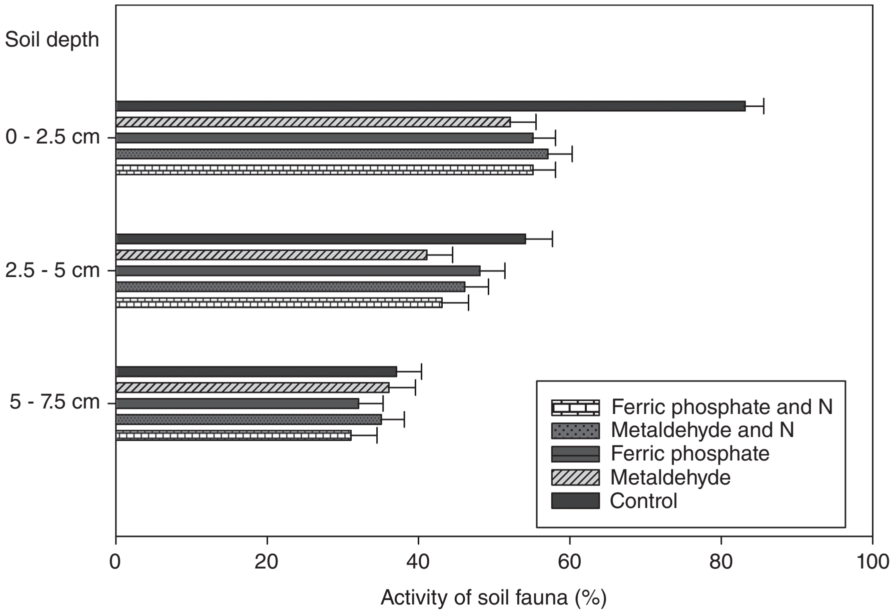

FIGURE 3 Feeding activity measured by bait-lamina sticks in a zero-tillage wheat field trial treated with either no slug pellets, TDS Major slug pellets (methaldehyde), Sluxx HP slug pellets (Ferric Phosphate—EDDS), or either slug pellets and Nitrogen at 30 kg ha^{-1}. There was a significant ($p < .05$) difference between the control and slug pellet treatments and in the depth of feeding activity.

(Figure 6b), with earthworms previously exposed ferric-phosphate slug pellets burrowing more deeply.

3.3 | Farmer consultation

The initial results were shared with 132 people attending three agricultural meetings, the majority of whom were farmers who were the sole or joint decision-maker on slug pellet use (SI Survey). The overall survey return rate was 52%. A total of 99% survey responders indicated they were 'interested' in the relationship between earthworms and slug pellet applications. In terms of detractor/passive/promoter characterization, the geographical groups were passive (0%–8% selected 'extremely interested') and the environmental group was a promoter (63% selected 'extremely interested'). The majority (72%–92%) of the audience 'mostly understood' or 'understood' the presentation. In terms of information quality, the majority 83%–92% rated the results as useful. In terms of information applications, the majority (76%) of the environmental group thought the results would impact slug control decisions, contrasting with a minority (28%–33%) of the geographical groups selecting that rating. In terms of personal decisions, these results were perceived as influential by all groups, reporting an intention to investigate IPM strategies or reduce slug pellet use. In terms of more research into earthworm—slug pellet interactions, thee geographic group were passive (71%–92% selected more research was needed) and the environmental group was a promoter (47% selecting 'urgent'). In terms of the credibility of using earthworms for the realistic monitoring of pesticides, the majority scored this as 'extremely' useful (environmental group), useful (geographical group) or 'very' useful (geographical group). This engagement type can be characterized as promotion (environmental) and passive (geographical groups).

4 | DISCUSSION

Farmers had an information need relating to reports that ferric-phosphate slug pellets were 'worm-friendly', which was brought to the attention of the last author. Published research indicated there were differences between pellet formulations (Edwards et al., 2009; Langan & Shaw, 2006). The purpose of this research activity was to help fill this knowledge gap. Ferric-phosphate formulations are used in both conventional and organic farming and at the time of the study were due to be the only approved chemical molluscicide (there had been an upcoming ban, and metaldehyde-based slug pellets are now banned in Great Britain). In terms of the first hypothesis, there was evidence to indicate that soil fauna feeding activities were reduced in the presence of slug pellets. The presence of slug pellets (metaldehyde or ferric-phosphate formulation), reduced soil fauna feeding activities (Figure 2), particularly in the surface horizon (Figure 3). The deployment strategy specifically targeted *L. terrestris* earthworm middens ($n = 5$ per plot), which are hotspots of biodegradation activities. This midden-based deployment strategy probably explains the sensitivity of this approach, formally recognizing *L. terrestris* redistribution of plant debris (and slug pellets) through nocturnal foraging activities, which results in highly localized hotspots. The two-point scale for bait consumption is biased towards earthworm activities because they are large, mobile invertebrates, which can consume 80–300 mg/g/day in food

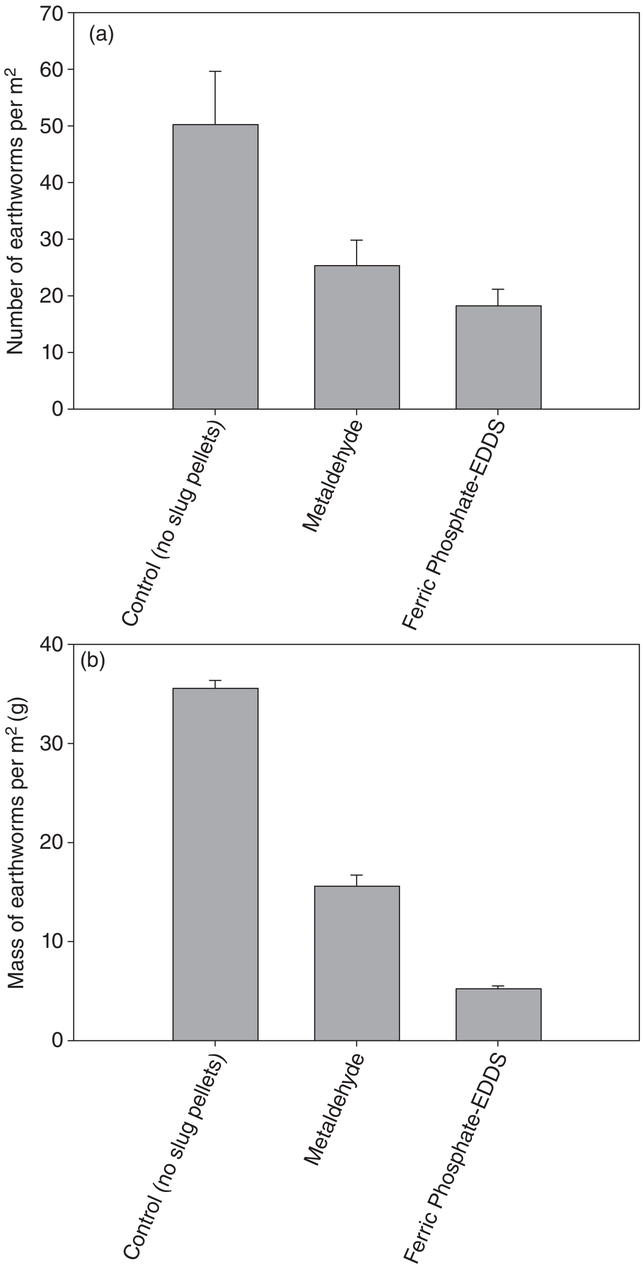

FIGURE 4 (a) Number of earthworms (b) mass of earthworms, extracted by a mustard vermifuge in a zero-tillage wheat field trial treated with either no slug pellets ($n=9$), TDS Major slug pellets (metaldehyde) ($n=9$), Sluxx HP slug pellets (Ferric Phosphate—EDDS) ($n=9$) 4 weeks after application. There was a significant ($p<.05$) difference between the control and slug pellet treatments.

(Edwards & Bohlen, 1996) and more likely to consume >50% bait (Vorobeichik & Bergman, 2021). There is no evidence that pest species of slug (*Deroceras reticulatum)* consumed the bait-lamina, no slugs were observed during field sampling. The presence of slug pellets was associated with lower numbers (Figure 4a) and biomass (Figure 4b) of earthworms on this field trial, which corresponds to an earthworm-mediated bait-consumption interpretation. The characterization of middens in the scientific literature indicates that they are foci of epigeic and endogeic earthworms, mesofauna and microfauna, with no documented observations of slugs (Butt & Lowe, 2007; Nuutinen et al., 2017; Schrader & Seibel, 2001). A detailed study of the slug *D. reticulatum distribution and locomotion in arable crops did not report any association with L. terrestris middens and tracking movement determined a maximum distance of 100 cm (*Forbes, 2019*). That is, it is likely that the soil fauna feeding activity response is linked to earthworm feeding activities.*

In the laboratory, individual *Lumbricus terrestris* earthworms consumed up to 4 slug pellets. However, there was no evidence to indicate that this resulted in mobility disorders. The exposure, regardless of formulation, did not significantly affect earthworm biomass (Figure 5) or burrowing activities (Figure 6a). Only exposure to ferric-phosphate-EDDS slug pellets increased burrowing depth (Figure 6b). This response could be a physiological reaction to this slug pellet formulation, triggering an avoidance response, which may help to explain the field findings (Figures 2 and 3; Figure 4a,b) of reduced feeding activity and surface abundance. Field earthworm populations were not significantly different to the control treatment at 4 months (although the abundance was low: <50 earthworms per m^2) indicating a temporary avoidance behaviour, for example, the earthworms may have moved down the soil profile (rather than away) when slug pellets are applied. Taken together, the results indicate a reduction in the effective food availability for earthworm predators such as birds, with implications for biodiversity. There may be concerns about long-term effects from the consumption of pellets, but this was beyond the scope of our study.

Standard ecotoxicological approaches investigate pesticide dose to mortality/reproduction relationships using compost-dwelling earthworm species (*Eisenia foetida*) and this information is publicly available (Pestici dePropertiesDatabase, 2018). Here we deployed a non-standard approach exploring feeding and burrowing activities at field-application rates on earthworms found in the field (*L. terrestris*) under the assumption this would be interesting to farmers. This has never been done before. Testing this assumption using a survey resulted in a response rate of 52% with the respondents reporting an interest in earthworm-pesticide interactions, ranging from passive (interest) to promoter (extremely) engagement characteristics (SI Survey). The midden-based experiment design was generally understood, which can be explained by stakeholders' knowledge about middens. A survey for the Agricultural and Horticultural Development Board found 83% farmers/agronomists ($n=111$) could correctly identify middens, and 86% knew that they were made by anecic earthworms

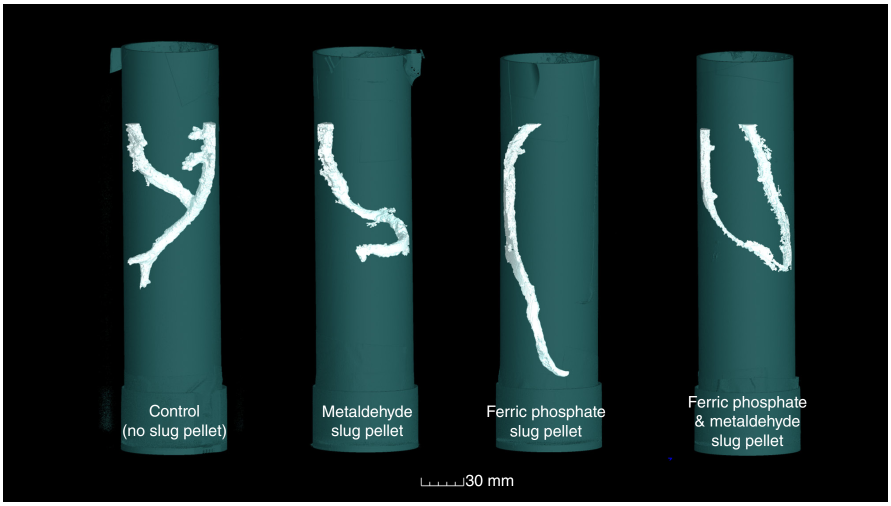

FIGURE 5 Example of earthworm burrowing characteristics after expose to slug pellets.

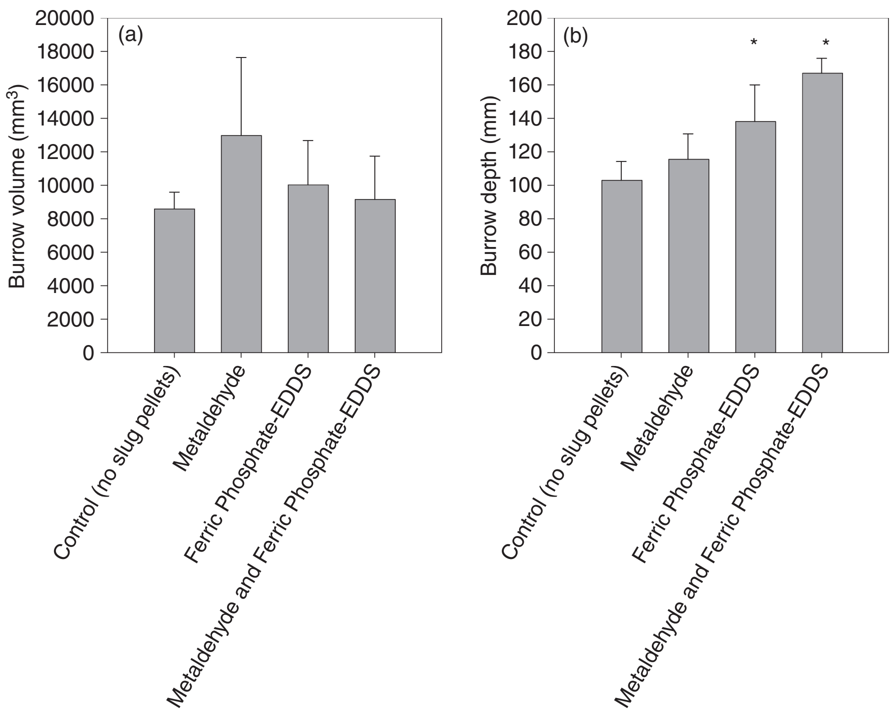

FIGURE 6 Laboratory burrowing assay ($n=3$, per treatment) (a) there was no significant ($p>.05$) difference in burrowing volume between earthworms previously exposed to slug pellets, but (b) a significant ($p<.05$) difference between the control and ferric phosphate-EDDS treatments in burrowing depth.

(Stroud et al., 2022). The majority (4 out of 5 respondents) rated the information about earthworm feeding/burrowing behaviours as useful, despite no corresponding data collection about slug control or crop protection. This is probably because the pesticide is widely known and used, we used field-application rates relevant to real-world management, and earthworm behaviours (feeding/burrowing activities) are beneficial to plant production (van Groenigen et al., 2014). In terms of personal decisions (and the majority of the respondents had sole or joint responsibility for slug control), these earthworm results were perceived as influential, with people reporting a voluntary intention to investigate Integrated Pest Management strategies or reduce slug pellet use. In terms of the latter, a better understanding of slug distribution and behaviours to precisely target (a reduction strategy) molluscicide applications would help to minimize non-target soil fauna exposure. In terms of the results being influential, it is in agreement with the interest in 'worm-friendly' pesticides, which provoked this research and indicates that our approach was aligned to farmers' information needs. There was no consensus as to whether these results would change general pesticide management decisions. This result can be explained by the wider context of these decisions (economics, trade-offs and barriers to best practice). Nonetheless, the respondents' consensus rated earthworm monitoring to measure pesticide impacts in the field as useful (which would explain the perceived influence of the results on personal decisions), with the environmental group rating it extremely useful, again consistent with a promotor characterization. This 'bottom-up' pressure for information is aligned to 'top-down' calls to overhaul pesticide risk assessment procedures to improve environmental realism, monitoring and stakeholder engagement (Topping et al., 2020).

5 | CONCLUSION

Metaldehyde-based slug pellets were finally banned for outdoor use in Great Britain from Spring 2022, meaning ferric-phosphate formulations are the only approved chemical molluscicide for use. We detected a reduction in earthworm feeding activity in the field, particularly in the top <25 mm soil surface and change in burrowing behaviour in the laboratory. Our results indicate that there is widespread interest in minimizing the effects of pesticides on non-target soil-dwelling organisms. Midden deployment is a promising strategy for measuring soil fauna feeding activities because they are biological hotspots and farmers have a good understanding of midden ecology. There is an important knowledge gap in terms of slug ecology, which could be used for the precise application of molluscicides, a strategy likely be of interest to farmers/advisors.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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