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Development of an environmentally sustainable and commercially viable approach to the control of the grey field slug, *Deroceras reticulatum*

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CONTENTS

1. Abstract

There is growing public and legislative pressure to reduce the use of pesticides in crop production. In arable fields, the grey field slug is unevenly distributed with patches of higher slug densities, interspersed within areas of lower slug numbers. Targeting molluscicide applications only at these patches (patch treatment), leaving other areas untreated, would substantially reduce molluscicide use for slug control. Building upon earlier AHDB funded work (student report 43), the aim of this study was to develop an approach by which these patches can be identified, and to develop a prototype patch treatment procedure that maintains effective slug control.

Extensive consultation with appropriate industry sectors (agronomists/farmers; soil assessment/mapping service providers; application technology/GPS manufacturers) informed all stages of the project. Liaison with industry players underpinned development of the patch treatment procedure through provision of advice on re-purposing soil assessment/mapping techniques and software for the system, state-of-the-art farm machinery, and commercial viability/constraints. Assessments were taken for field experiments by industry colleagues, and anonymised commercial datasets provided for analysis.

Of seven soil characteristics investigated, significant relationships were established between slug patch location and %clay, %silt, and soil organic matter. The cost of soil analysis can be reduced by using electroconductivity scans as a proxy for soil structure. Further testing in 2020/21 confirmed these relationships, demonstrating their potential to predict patch location. Field tests of a provisional patch treatment protocol showed that, in comparison to treating whole fields, patch treatment resulted in similar residual post treatment slug populations during the crop damage window, but with only 30% of the area receiving pellets.

Slug patch location was found to be stable providing a ‘standing target’ for control measures. Variation of soil structure factors across fields was stable for periods of up to eight years (despite regular cultivation), with organic matter also stable in unimproved fields. Thus, historical assessments can be used for patch treatment targeting avoiding the need for annual re-assessment and allowing re-use of soil maps made for other husbandry purposes.

A prototype patch treatment procedure was developed, which initial analysis shows results in considerable savings in the total crop area treated, addressing the sustainable crop production agenda. The principle operational costs are low, as the required soil assessment/mapping approaches are already used for other husbandry purposes, and the protocol uses available machinery/software. Savings, accrued from reduced molluscicide usage, have been incorporated into an initial cost-benefit analysis, which shows that the procedure has a positive effect on gross margin budgets for winter oilseed rape.

2. Introduction

The grey field slug, *Deroceras reticulatum* (Müller), is a widespread and economically important pest in temperate regions throughout the world, damaging a wide range of field crops (Kozlowski *et al*, 2014; Ramsden *et al*., 2017). In the UK, slugs are considered to be one of the most damaging pests of arable crops and, in the absence of effective control, it is estimated that they would cost the industry up to GBP 100 million per year (Nicholls, 2014; Twining *et al*., 2009). Management in most arable crops relies on conventional molluscicides applied as pellets to the soil surface and usage of these products fluctuates between years and regions in relation to environmental factors such as autumn rainfall. Average usage is usually high; however, for example, in 2018, a total of 471,872 ha wheat and 390,828 ha oilseed rape each received a mean of two applications of molluscicides, while 55,745 ha potatoes received between 2 and 3 applications (27, 67 and 39% of total crop areas respectively; Garthwaite *et al*., 2018). A biological control agent for slugs (the nematode *Phasmarhabditis hermaphrodita*) is also available but, in the UK, use of this option is generally confined to high value horticultural crops and it is currently not cost effective in crops such as cereals or oilseed rape (Glen *et al*., 2000; Wilson *et al*., 1996, 2005).

There is growing public and legislative pressure to reduce the use of conventional control agents in crop production, due to their contribution to air, soil and water pollution, and as a result of perceived risks of environmental damage or adverse effects on human health (Alavanja *et al*., 2013; Defra, 2015; EC, 2020; Hillocks, 2012; Jepson *et al*., 1990; Pimental & Greiner, 1997). The limited number of active ingredients available for slug control in Europe has been exacerbated by the loss of approval for Methiocarb in 2015, and Metaldehyde (currently the subject of national restrictions) which is due to be phased out by March 2022, (Twining *et al*., 2009). Use of the few available molluscicides on such large scales, therefore, make new approaches to sustainable use of the products a high priority.

The current recommended practice for slug control is to use refuge traps to assess slug pressure and apply pellets when the number of slugs found in traps exceed a threshold level (AHDB, 2018), but this method of monitoring is thought to lack accuracy. For example, the number of slugs caught in traps has been found to vary depending on environmental conditions such as temperature and moisture, which are known to affect slug activity and behaviour, thus reducing their accuracy when assessing population level (Choi *et.al.,* 2006). There is anecdotal evidence that some farmers have responded to such uncertainties and the costs of the trap/threshold approach by applying slug pellets only to areas of the field where they believe slug pressure is higher ("patch treatment"). This method of pellet application is based on historical knowledge of the field and where areas of damage regularly occur (at-risk areas). The use of such crop damage assessments in place of refuge trapping has been investigated in the USA but only a weak correlation between slug numbers/patches and damage level was reported, questioning the reliability of the approach (Mueller-Warrant *et.al.,* 2014).

More widely, the potential for reducing pesticide use on farms by spatially targeting applications to specific areas of arable fields to control pest and weeds has attracted repeated interest (e.g. Archard *et al*., 2004; Brown *et al*., 2008; Pimental, 1997; Sotherton *et al*., 1993), with studies investigating a range of approaches including, amongst others, use of the probability of encountering target species in a spatial environment, development of field contour maps of defined thresholds, and automated robotic pesticide spraying over target areas (Brenner *et al*., 1998; Fleischer *et al*., 1999; Sammons *et al*., 2005). *Deroceras reticulatum* is known to display a heterogenous distribution in arable crops, characterized by discrete patches of higher slug densities dispersed across the field with fewer slugs in intervening areas (Bohan *et al*., 2000; Forbes *et al*., 2017; Hillocks, 2012; Mueller-Warrant *et al*., 2014; South,1992). This may offer the potential for targeting molluscicide treatments only at higher density patches, but successful use of the technique relies on an understanding of several key factors, including the degree of spatio-temporal stability of the patches and the biological mechanisms underpinning patch cohesion. In addition, the range of patch sizes encountered and frequency of occurrence should facilitate the automation of targeted treatment across fields, and an approach incorporating action thresholds into a commercially viable management procedure for patch treatment is required. Such a procedure will also rely on the development of a commercially viable method of identifying patch location and dimensions.

A recent AHDB project (no. 2140009118) yielded empirical work conducted in the major crop growing regions of the UK which confirmed the existence of slug patches in all commercial fields investigated (Forbes *et al*., 2017). Populations of *D. reticulatum* are, however, distributed between the soil surface and the upper soil horizon, with a smaller proportion being active on the surface during periods of sub-optimal temperatures or dry weather (South, 1992). The large but variable proportion that are located within the upper soil horizons cannot be easily detected using the standard surface refuge traps used in these experiments. Slug patches identified during periods with favourable conditions were, therefore, found to be difficult to locate during periods with adverse weather but re-appeared in the same locations as conditions improved, demonstrating potential temporal stability (Forbes *et al*., 2017). This conclusion was supported by studies of the movement of individual slugs in field crops, which have shown that most forage within a limited area (Forbes *et al*., 2020). Recent work has provided an insight into an underlying mechanism leading to this observation, by showing that components of slug movement (average velocities, turning angles and movement/resting times) vary between slugs in higher and lower density areas, resulting in them dispersing more slowly when in higher density patches of conspecifics (Ellis *et al*., 2020). Confirmation of the spatio-temporal stability of slug patches in arable crops, however, awaits detailed analysis of empirical field data from commercial crops in different cropping years. Modelling studies based on extensive empirical field data have also demonstrated that the range of patch sizes encountered and their frequency of occurrence permit the automation of targeted treatment across fields (Petrovskaya *et al*., 2020).

The AHDB project also investigated slug patch formation in relation to seven candidate physical characteristics of the soil, and a subset were collectively found to be related to their location in commercial crops. It was proposed that in combination, a sub-set of these soil characteristics might be used to predict where slug patches will form in commercial crops providing an alternative, more accurate approach to targeting patch treatments

This study extends the findings of the earlier work in three key areas which require investigation before development of a prototype patch treatment approach for slugs can be developed. Firstly, empirical data collected from commercial arable fields is used to investigate the potential of using the seven candidate soil characteristics identified in the earlier work to predict the location of patches of higher slug numbers in a practical patch treatment system. Secondly, detailed analysis of datasets is undertaken to confirm the extent of spatio-temporal stability of slug patches in commercial arable fields in different crop growing regions of the UK and different cropping years. Thirdly, the integration of a patch treatment approach with current threshold-based decision making for treatment application has been addressed, and the extent by which the new system would reduce pesticide applications established. Based on these and previous findings, a prototype system is proposed which has been tested in winter wheat fields, and an outline gross margin budget calculated.

3. Materials and methods

The core methodology for field studies utilised techniques developed during delivery of earlier AHDB-funded research investigating the potential for patch treatment of slug infestations of field crops (AHDB project no. 2140009118), thus ensuring all datasets were directly comparable.

3.1. Consultation with industry

Effective development of a practical, commercially viable approach to patch treatment depended on close interaction wth several industry sectors throughout all stages of the work programme.

Objective 1 of the project required the establishment of “a network of contacts from all relevant industry sectors (farmers, agronomists, equipment and pesticide manufacturers, soil mapping companies, etc.) to comment on, guide and participate in all aspects of the project, ensuring scientific and commercial feasibility of the outcomes, and maximising potential uptake of the findings”.

The objective was addressed under work package (WP) 1 and required regular communication with multiple stakeholders in diverse specialist fields. To achieve this efficiently, a structured stakeholder engagement plan was developed in which leading/influential companies or individuals from each required industry sector were identified and primary interaction was focused on these contacts. Knowledge exchange within each sector and the essential two-way discussion benefited from the key companies/individuals being recognised as commercial experts, thus promoting acceptance in the wider agricultural community, and in most cases acting as conduits for wider communication. The approach was also intended to reduce barriers to the adoption of new technologies by introducing and discussing new concepts openly and at an early stage, with providers that had a track record of successful innovation. This led to early recognition of commercial constraints that we needed to take into account in the developing system.

The approach adopted involved segmentation of industry sectors, and was implemented in three stages. The first stage defined the central industry sectors with which the project needed to communicate closely. In the second stage, the characteristics of the primary stakeholders were discussed and both the information or support they could provide to the project, and the information generated from the project that would be of value to them, were identified. Based on this analysis, a shortlist of organisations or individual stakeholders who may be approached was established for each sector.

The initial stakeholder list was then reviewed and amended to identify potential primary stakeholders, and they were partitioned into communication segments with comparable interests in the work, forming a segmentation matrix of the candidate representative bodies for each segment. In each case the breadth of representation and specialist interests relevant to the project were identified to ensure the selection adequately covered the project needs. While doing this, relevant individuals/bodies (including AHDB contacts) were consulted for advice regarding who to approach, and interest expressed by various companies (or individuals) was also considered. In each sector one or more representative organisation was identified to represent the segment.
The second stage was completed by re-visiting the specific aspects of the project's research work of importance to each segment/representative body and following this, their potential involvement was defined by the assistance that we sought from them, and the information etc. that may need to be imparted to them

In the final stage a practical approach to engagement was established. Communication pathways for each sector were identified (i.e. best media for active communication), and a contact/lead individual for each the representative body who would act as “driver” for their sector was identified. Initial contact was made and agreement to become involved obtained.

3.2. Development of a procedure for predicting locations in which slug patches will develop

3.2.1. Assessment of slug distribution

The design of a sampling technique that accurately locates slug patches without prior knowledge of the spatial pattern of population distribution, is problematic. This study used the monitoring approach developed for use in AHDB project (no. 2140009118), ensuring all data is directly comparable (Petrovskaya *et al.*, 2018). In each field, an area of 1 ha was sampled using a 10 x 10 grid of refuge traps (10 m inter-node distance) to assess slug abundance/activity on the soil surface. The minimum distance between the grid and the field boundary was 20 m, and to facilitate its re-establishment in different crops in the rotation, it was mapped using a Global Positioning System (Leica RX1220T, Wetzlar, Germany). The minimum distance from field boundaries reduced the potential for the perimeter to core slug density gradients previously reported in arable fields to differentially affect the accuracy of patch identification across the trapping grid using surface refuge traps (South, 1992).

Traps consisted of upturned 18 cm diameter terracotta plant pot saucers (LBS Horticulture Supplies, Lancashire, UK), without bait to avoid slug feeding attraction. At each assessment, the number of *D. reticulatum* found under each trap in the sampling grid (i.e., on the soil or the surface of the trap) was recorded, the trap was immediately re-set and any slugs caught were released beneath it.

3.2.2. Soil analysis

Experimental work conducted under AHDB project no. 2140009118 identified a range of candidate edaphic characteristics that potentially affect the location of slug patches in the field. Selection of the characteristics for further study was based on a range of biological and practical considerations, the latter informed by detailed discussion with and commercial recommendations of the soil mapping company Precision Decisions. The initial list was reduced by eliminating any that would be impractical for commercial use, for example direct measurements of the moisture content or temperature of the upper soil horizons both of which are subject to rapid temporal variability. The remaining candidate factors were further considered in relation to soil characteristics regularly used on many farms for other agronomic purposes, to facilitate cost-sharing. In addition, selection criteria included the frequency at which these existing assessments were repeated, and the physical distance between assessment points (resolution) to ensure they met minimum requirements for slug patch location.

Initial screening of slug populations was conducted in the 2019-20 growing season in 19 fields distributed across major cereal and oilseed rape and potato growing regions in the UK, including Cheshire, Shropshire, Yorkshire, Lincolnshire, Nottinghamshire, Wiltshire and Hampshire (Figure 1). Trapping grids were established, and between two and five slug assessments were carried out in each field between November 2019 and March 2020, and the areas of higher and lower slug densities were identified using the approach of Forbes *et al*. (2021), see also section 3.4.2 below.

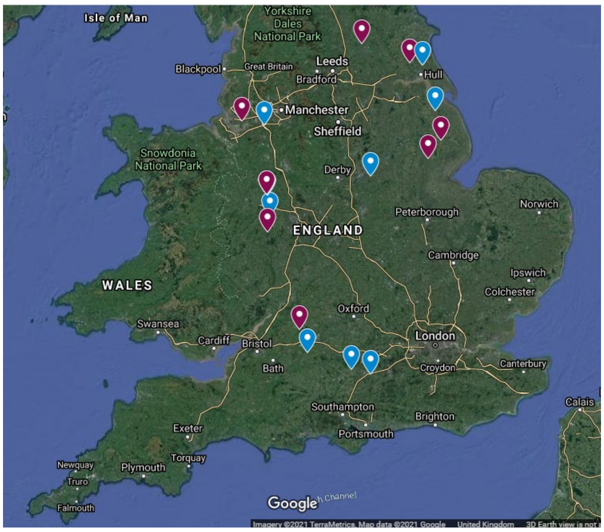


Figure 1. The location of the 19 field sites used in the 2019-20 and 2020-21 field seasons. Each field was pre-screened to identify those with higher slug populations. Blue markers: field sites with lower slug numbers; Purple markers field sites with higher slug numbers; three markers show the locations in which two pre-screened fields occurred in close proximity to each other.

Following the initial screening of slug populations, soil samples were collected from the eight fields with the highest slug populations, which were located in Shropshire, Lincolnshire, Yorkshire, Cheshire and Wiltshire (Figure 1). Thirty soil samples were taken within each sampling grid from a range of points within areas displaying consistently high or low slug numbers With the exception of the field site near Malmesbury, two soil samples were taken at each sampling point, one for assessment of bulk density and one for investigation of other soil characteristics (see below). At the Malmesbury site the sample for bulk density analysis was not taken due to notification during an assessment visit (when the necessary equipment was not available) of imminent recultivation following crop failure.

The methodology for analysis for the various edaphic characteristics selected, followed the standard approaches used in AHDB project (no. 2140009118), facilitating direct comparison of results. Soil samples were prepared for analysis by air drying at 35°C for a minimum of 96 hours before grinding and sieving them through a 2 mm sieve.

Assessment of pH:

A 10g sub-sample of soil was added to 50 ml water and shaken in an orbital shaker (HS 501 digital, IKA, Germany) at 240 RPM for 15 minutes. Assessments were made using pH meter (3510 pH meter, Jenway, UK) that was recalibrated after every 50 samples using pH 4.0 (Buffer Colour Coded Solution pH 4.00 (Phthalate) Red, Fisher Scientific, UK) and pH 7.0 buffer solutions (Buffer Colour Coded Solution pH7.00 (Phosphate) Yellow, Fisher Scientific, UK), and following a standard recommended approach (Ministry of Agriculture, 1986).

Organic matter

A 10 g sub-sample was added to a pre-weighed crucible, before being dried in an oven at 105°C (LCO/42H/DIG, Genlab, UK) for 24 hours, after which the weight of soil was recorded to the nearest 0.1 µg (Precisa 262SMA-FR, Precisa Ltd, UK). The sample was then placed in an ashing furnace (AAF11/18, Carbolite Gero, UK) for 4 h at 450°C before being allowed to cool in a desiccator and reweighed (Ministry of Agriculture, 1986). The organic matter content was calculated using the equation:

Organic matter % = ((dry weight – final weight) x 100)/dry weight

Soil texture

Analysis of soil texture followed standard procedures (Ministry of Agriculture, 1986; Kettler et.al., 2001; Tan, 2005). Hydrogen peroxide (20 ml) was added to air dried and sieved soil (10 g) and left to soak for a minimum of 15 hours. An additional 10 ml hydrogen peroxide was then added and the soil heated on a hot plate (SD 500 digital hotplate, Stuart Equipment, UK) set at 90°C for one hour, with the soil stirred at 10-minute intervals and the volume maintained at 25 ml by adding distilled water as required. The solution was then boiled for 2 minutes to complete the breakdown of organic matter before being allowed to cool to laboratory ambient temperature. Dispersing agent (10 ml; 35 g sodium hexametaphosphate and 7 g sodium carbonate in 1 L distilled water) was then added to the solution and shaken on an orbital shaker (HS 501 digital, IKA, Germany) at 240 RPM for ten minutes. Dispersing reagent (10 ml) was added to a pre-weighed crucible and placed in a 60 °C oven for 24 hours before being reweighed and the Residue weight calculated

After shaking, the remaining mixture was sieved through a 63 µm sieve. The contents of the sieve were transferred into a pre-weighed crucible and oven-dried (60°C; Sample a). The contents of the measuring cylinder were made up to 500 ml and mixed thoroughly. A 25 ml sample was taken from 90 mm depth and transferred to a pre-weighed crucible and oven-dried (60°C; Sample b). After the solution had been allowed to settle for 7.5 hours, a second 25 ml sample from 90 mm depth was taken, transferred to a pre-weighed crucible and oven-dried (60°C; Sample c). The samples were reweighed at 24-hour intervals until they reached a constant weight, after which the weights for sand (sample a), silt (weight sample b minus sample c) and clay (sample c) were recorded.

Initial sample weight = Sample a + Sample b – Residue weight
Sand % = (Sample a / initial sample weight) * 100
Silt % = (((Sample b * 20) – (Sample c * 20) -Residue weight) /Initial sample weight) * 100
Clay % = (((Sample c * 20) -Residue weight) / Initial sample weight) * 100

Bulk density

Bulk density was determined using the method of Wood (2006). At each sampling point a soil core (7.5 cm diameter x 7 cm height) was taken, its volume calculated ($\pi r^2 h$). The soil was returned to the laboratory and dried for 72 h (or until a constant weight was recorded in successive assessments) at 105°C in an oven (LCO/42H/DIG, Genlab, UK). Bulk density was calculated using the equation:

Bulk density = dry weight of soil (g) / volume of soil (ml)

Particle Density

Particle density was determined using the method of Tan (2005). Oven dried and sieved soil (40 g) was placed in a pre-weighed 100 ml flask and the weight recorded before 50 ml of water were added. The mixture was allowed to stand for 5 minutes before the total volume was recorded. The total volume of soil solids and particle density was calculated using the equation below.

Particle density = oven dry weight of soil (g)/ volume of soil (cm^3)

3.2.3. The effect of soil structure, organic matter, soil pH on the location of patches of higher slug density in arable fields

To investigate the effect of the selected soil characteristics on slug numbers and slug patch location (WP 2) a negative binomial mixed effect generalised linear model (glm) was used. Field was included as a fixed effect to account for repeat sampling within individual fields. The soil texture components (percentage sand, silt and clay) were log transformed to ensure a standard scale for all the independent variables. Factor reduction was used to determine the minimum adequate model. Residuals were checked to ensure the assumption of homogeneity of variance was met.

A logistic regression analysis (a statistical method for assessing the effect of independent variables on a binary dependent variable) was used to confirm the model was sufficiently accurate for determining a binary decision of whether to apply treatments or leave an area untreated based on a threshold of ≥4 slugs per trap.

Maps of each soil characteristic and slug distributions were created using the interp and filled.contour functions in R, the values between sampling points were estimated by polynomial interpolation.

3.3. Testing the procedure for predicting slug patch location in major arable regions

In order to establish whether the edaphic factors (soil texture, organic matter and pH) identified under sections 3.2.1, 3.2.2 and 3.2.3 of this report are sufficient to predict the location of areas of higher slug numbers, two approaches were used.

3.3.1. Using soil characteristics to predict areas with higher slug numbers

In the 2020-21 field season, 10 arable fields from a wide geographical range across major UK cereal and oilseed growing regions, which had been identified by the grower as fields which were susceptible to slugs, were investigated (Figure. 2). From these fields it was intended to select up to three with sufficiently high slug numbers to facilitate informative testing of the procedure.

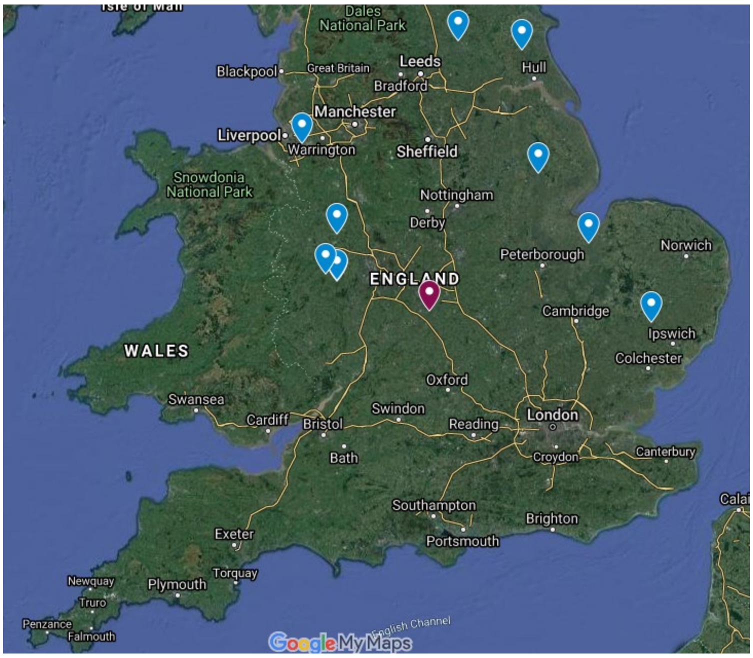


Figure 2. The location of 10 field sites used during the 2020-21 field season. Each field was pre-screened to identify those with higher slug populations before a subset were selected for further investigation. The purple dot shows the location of the field site used in a later study to compare patch treatment with whole-field treatments slug population suppression (section 3.3.2).

Following discussion with the soil mapping company Precision Decisions, electroconductivity (EC) scans (in lieu of soil texture, see Figure 3 for an example) were used to identify 20 areas across each field in which either high or low slug numbers were predicted. Soil samples were taken from these points and soil structure characteristics were analysed (as described above in section 3.2.2), enabling comparison with the soil maps. EC scans can be used to identify areas of a field with different soil properties as electroconductivity is directly affected by soil moisture. Areas of relatively heavier or lighter soil within the field are reflected in the scans, as smaller clay particles conduct more electrical current than larger silt and sand particles. As soil structure affects moisture retention, EC scans can be used as a proxy for soil structure as they indicate areas within fields of relatively high moisture content (reflecting the underlying soil moisture retention characteristics). Thus, if they can be used to forecast areas that are generally prone to higher or lower moisture levels within fields, as slugs also respond to soil moisture levels/moisture retention characteristics, they may also be used to predict locations in which slug patches will form.

Using the model identified in section 3.2.3 and the predict function (in the car package in R) the predicted *relative* number of slugs at each of the 20 sampling points in each field were estimated from the results of the soil analyses, in order to predict areas of higher slug densities. To confirm the accuracy of this prediction model slug traps were placed at these points (terracotta plant pot saucers as described in section 3.2.1), and either 2 or 3 slug assessments were carried out in each field during February and March 2021. The precise number of slug assessments varied due to travel restrictions resulting from the Covid-19 pandemic. Identification of areas of fields with higher slug densities is difficult using surface refuge traps when there is low surface activity of slugs at the time of assessment (Forbes *et al*., 2021).

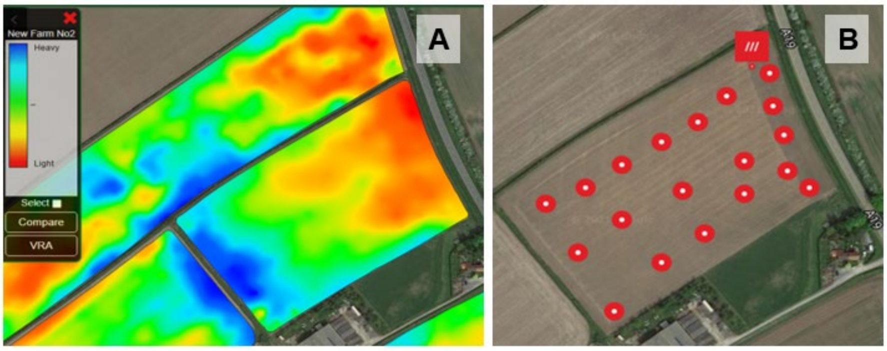


Figure 3. The use of Electroconductivity (EC) scans as a proxy for soil structure. (A) EC scan of a field near Shipton (Yorkshire), prepared using commercial procedures by Precision Decisions Ltd. The scale shows the conductivity range, with blue representing areas of higher conductivity (heavier soils) and orange those with lower conductivity (lighter soils). (B) Red circles indicate the location of soil samples (October 2020; laboratory analysis of soil characteristics) and slug refuge traps (February and March 2021).

To ensure that the most damaging slug patches were not missed, in the fields used in the analysis the maximum number of slugs caught in an individual trap was ≥4 (based on the mean trap count across the different sampling dates; the current AHDB action threshold) and the mean count for each trap was compared to the predicted values using linear modelling and Pearson's product moment coefficient (Crawley, 2013).

To determine the success of a model in predicting the location of higher density slug patches using edaphic factors an approach was adopted in which the outcome was scored on a binary scale, successful or unsuccessful. The binary dependant variable, success, which was assigned a 1 if that sampling point reached a presumptive definition of a "high slug density" of ≥4 slugs/trap (reflecting the AHDB action threshold) or 0 if the threshold was not met (see section 3.2.3). The data were analysed using a mixed effects logistic regression model and a prediction model was created using machine learning (Radecic, 2020). The dataset from the 2019-20 season was split into a training and test set using the samplesplit function (in the caTools package in R). The model was determined using the training set, and then using the predict function and the test set, predictions regarding whether the sampling point exceeded the presumptive treatment level or not were made. The confusionMatrix function (in the caret package) was used to determine how successful the model was at predicting the requirement for treatment of areas of the field with higher slug densities.

The same prediction model was applied to the data from the 2020-21 fields, again using the presumptive (experimental) definition where the maximum number of slugs per trap was ≥4. The rate of successful prediction of such patches, and the number of false positives and false negatives, was calculated as a percentage and used to assess the accuracy of the prediction model for new fields.

The negative binomial mixed effects model (described in section 3.2.3.) was also applied to confirm the variables which were having an effect on the number of slugs per trap in the 2020-21 season.

3.3.2. Testing the patch treatment approach on an AHDB strategic farm

The viability of patch treatment for slug control, the proportion of the field left untreated (thus the reduction in pesticide applied/potential financial saving), and the risk of significant damage resulting from surviving slugs from the untreated areas, were tested on an AHDB Strategic farm (WP 3). Both the number of trials conducted and the number of field sites available for pre-scanning to support selection of crops with large slug populations was restricted due the COVID-19

Two grids, each consisting of 100 refuge traps (as described in section 3.2.1.) were established in a winter wheat crop. The grids were situated in areas of the field where soil texture (identified from Electroconductivity (EC) scans, slope and distance to the field margin were similar.

Two slug counts were carried out in each grid on days following favourable weather conditions for slug surface activity (12/10/2020 and 14/10/2020), to establish slug numbers and patch location prior to the growers' decision to apply slug pellets to the wider field. Areas of each grid with higher slug numbers were identified from distribution maps (created using the interp and filled.contour functions in R) using the method of Forbes *et al*. (2021). In one grid a uniform application of slug pellets was applied on 16th October 2020, to coincide with pellet application to the surrounding crop (the timing of which was decided by the grower). In the second grid, only the areas around grid trapping nodes (related to GPS coordinates) shown to have higher slug numbers were treated. Treatments used the product/rate selected and applied to the surrounding field by the farmer (7kg/ha of ferric phosphate as Sluxx HP, Certis, UK). Two post-treatment assessments of slug numbers were carried out at 4 and 17 days after application.

3.4. Testing soil characteristic and slug patch stability

3.4.1. Spatio-temporal stability of soil characteristics

A technique using layers of soil maps to locate slug patches was investigated but to be commercially viable this requires the soil characteristics used to have sufficient spatio-temporal stability to support accurate predictions, without the need for frequent resampling with associated labour and cost implications.

To investigate soil characteristic stability (and thus the frequency of resampling/re-assessment required; WP 4), comparison of a series of soil samples taken from the same sampling grid but spanning two cropping cycles were originally planned. This was to be achieved cost-effectively by taking soil samples and slug assessments after cultivation/sowing of a new crop, from the 8 fields investigated in work reported in sections 3.2.2 and 3.2.3. Statistical comparison of the predicted locations of slug patches in each cropping season would have been validated by establishing their actual locations using trap counts. The work was prevented, however, by travel restrictions during the Covid-19 pandemic. The data gap was mitigated by utilising data provided by Precision Decisions, and from fields studied during the previous project (AHDB no. 2140009118).

Records from the previous project yielded datasets describing soil characteristics from samples taken within a GPS referenced 100 x 100m sampling grid established in commercial crops during the 2016/17 and 2017/18 cropping seasons from a field in Shropshire (Adeney) and another from

Leicestershire (Oadby; see also Forbes *et al*., 2021). Analysis of data from different cropping years was carried out to assess whether the current commercial practices in soil mapping reflected the frequency at which they would need to be assessed (annually, at intervals of multiple years, etc.) to accurately predict slug patch location.

Analysis of historical data from designed experiments – Soil pH and organic matter content

To investigate the between year stability of pH distributions in arable fields, data from AHDB project (no. 2140009118) was reanalysed. Soil pH of samples taken from the trapping nodes of a standard sampling grid (see section 3.2.1 and Forbes, 2019) established in two fields in Shropshire (Adeney) and Leicestershire (Oadby) were analysed using the method described in section 3.2.2. In each field sampling had been carried out in two consecutive years (2016 and 2017), and GPS readings ensured that the grid was established in the same position in each case. Assessments of pH were compared between seasons using Pearson’s correlation coefficient. Organic matter content of the soil samples taken from these fields was also established (using the method described in section 3.2.2) and subjected to a similar statistical analysis.

Analysis of commercial field scans – Soil texture and soil pH

Temporal stability of soil characteristics can vary between farming systems, for example organic systems can result in greater stability of pH than some conventional systems (Schramaa *et al*. 2018). However, studies suggest that mean levels across fields of characteristics of interest to this study may be stable between years. To investigate the within-field spatio-temporal stability of soil texture and soil pH both of which influence the location of patches of higher slug numbers in arable fields, soil assessment data collected from two commercial fields were provided by the soil mapping company Precision Decisions. All data was anonymised to protect client confidentiality and collected using the standard commercial techniques and resolution used by the company.

In the first field, commercial electroconductivity scans (soil texture) were conducted twice (2009, 2017), and with an 8 year gap between assessments. The data from each year were mapped using the interp and filled.contour functions in R, and the maps compared using Pearson’s correlation coefficient.

In a second field, located in Yorkshire, soil pH was assessed three times over an 8 year period (in 2011, 2015 and 2019) by soil sampling at regular intervals coupled with subsequent laboratory analysis using a method similar to that described in section 3.2.2. Soil maps were again produced using the interp and filled.contour functions in R, and data compared using Pearson’s correlation coefficient.

3.4.2. Spatio-temporal stability of slug patches

Historical data collected using the sampling procedure described in section 3.2.1 above was analysed to establish the spatio-temporal stability of slug patches (WP 4). Sampling had been conducted in three consecutive growing seasons in commercial crops from major UK arable regions. Each crop was grown as part of rotations that included oilseed rape and wheat, and as position in a rotation can affect slug numbers (Nicholls, 2014), both the crop sampled and the preceding crop were recorded (Table 1). In all cases normal agronomic practices for the farm were followed. Work was conducted in 5 fields in Shropshire in year 1 (November 2015 - May 2016), 12 from a wider geographical area in year 2 (August 2016 – June 2017; Eastern England: Lincolnshire; Central England: Nottinghamshire, Leicestershire; Western England: Shropshire, Lancashire), and 5 in year 3 (September 2017 – June 2018; - Eastern England: Lincolnshire; Central England: Leicestershire; Western England: Shropshire, Lancashire). Re-sampling a sub-set of experimental fields in different years facilitated comparisons between successive crops (Years 1-2 = 4 fields; Years 2-3 = 2 fields; Years 1-3 = 1 field), and the field codes defined in Table 1 identify those in which these sequences occurred. Such resampling resulted in a total of 15 different fields and 22 different crops being studied, the latter comprising 6 different crop types.

Table 1*.* Location, field codes and crop rotations of experimental field sites in each year of the study. Crops in bold were used in the analysis; crops in italics were grown prior to the commencement of experimental work.

County (Field Code)	**Location (Nearest Town/ Village)**	**Cropping season**			
		2014-15	**2015-16**	**2016-17**	**2017-18**
Shropshire (Shrops 1)	Adeney (1)	*Oilseed rape*	**Winter wheat**		
Shropshire (Shrops 2)	Adeney (2)	*Oilseed rape*	**Winter wheat**	**Winter barley**	**Oilseed rape**
Shropshire (Shrops 3)	Lynn (1)	*Oilseed rape*	**Winter wheat**	**Fallow**	
Shropshire (Shrops 4)	Lynn (2)	*Oilseed rape*	**Winter wheat**	**Fallow**	
Shropshire (Shrops 5)	Uppington (1)	*Oilseed rape*	**Winter wheat**	**Fallow**	
Leicestershire (Leic 1)	Oadby		*Oilseed rape*	**Winter wheat**	**Cover crop (black oat/phacelia)**
Leicestershire (Leic 2)	Hoby		*Oilseed rape*	**Winter wheat**	
Lancashire (Lancs 1)	Wigan		*Oilseed rape*	**Winter wheat**	**Fallow**
Lincolnshire (Lincs 1)	South Kyme (1)		*Oilseed rape*	**Winter wheat**	
Lincolnshire (Lincs 2)	South Kyme (2)		*Spring wheat*	**Spring wheat**	
Lincolnshire (Lincs 3)	Dog Dyke		*Winter wheat*	**Winter wheat**	
Nottinghamshire (Notts 1)	Flawborough		*Oilseed rape*	**Winter wheat**	
Shropshire (Shrops 6)	Bridgnorth		*Winter wheat*	**Oilseed rape**	
Shropshire (Shrops 7)	Uppington (2)			*Oilseed rape*	**Winter wheat**
Lincolnshire (Lincs 4)	Belchford			*Spring beans*	**Winter wheat**

Hotspot Analysis

Slug distributions within the trapping grids used in the assessments in all fields were visualized for each sampling visit to the 22 crops studied using grid maps of counts, generated using the interp and filled.contour functions of R, with the number of slugs in areas between traps estimated by polynomial interpolation. The spatial distribution of slugs caught in the refuge traps within each sampling grid was investigated by identifying statistically significant spatial clusters of higher numbers of slugs using the ScanLRTS function in R. The ‘observed’ distribution (estimated from trap counts) was compared to that ‘expected’ if a homogenous distribution of those slugs was assumed. Areas of significantly higher ($p < 0.05$) than expected slug numbers (hotspots) were highlighted in the visualized grid maps. Data collected during individual assessment visits to each field site were analyzed separately and the number of visits in which significant hotspots occurred were identified and recorded.

Slug Clustering and Patch Stability

To assess the spatial stability of areas of higher slug numbers (patches), following tests for normality, the effect of trap (location within the grid) on slug numbers for each of the 22 individual crops studied was subjected to a Poisson GLM mixed effects model, and the ANOVA function in R was used to extract the main effects. Analysis was conducted using R version 3.2.3 (R Core Team., 2012). Within each field in which statistically significant effects of trap location on number of slugs caught was found, the correlation between all combinations of sampling grid assessments was then determined using Mantel’s permutation test (Mantel 1967).

3.5. Practical assessment of soil characteristics

The cost of taking dedicated soil assessments to provide input data for the procedure developed to predict the location of patches of higher slug numbers, thus facilitating the targeting of molluscicide treatments, would be higher than the savings achieved by only treating a limited area of a field. Accordingly, the potential for re-using soil assessments already taken for other on-farm purposes was explored with industry collaborators (WP 5).

3.5.1. Current technology/approaches for assessment of the selected soil characteristics in commercial practice

The soil assessment and soil mapping company Precision Decisions was consulted to determine current commercial approaches used for assessment of the selected soil characteristics (soil texture, organic matter content and pH), and the frequency with which the company was commissioned to provide assessments of each of the edaphic factors of interest. These discussions were later supplemented by conversations with a second company, Hutchinsons Ltd.

Electroconductivity scans are frequently carried out to support farm-specific husbandry decisions, and can be used as a proxy for soil texture (see sections 3.3.1 and 3.4.1). As EC varies according to soil moisture content and % sand and % silt affects moisture retention, and as the prediction of locations in which patches of higher slug numbers will develop also relies on relative moisture retention, the spatial variation in readings will reflect the soil texture and potential locations of slug patches

Assessment of pH and organic matter content of soil is also regularly assessed on farms, with legal requirements for a maximum interval between pH assessments (five years) currently in place. Assessments require soil sampling and laboratory measurement using technique described in section 3.2.2.

Regular discussions with industry contacts throughout the project also identified how each of the selected soil characteristics are currently mapped, the resolution of the maps produced (sampling interval across the field), the recommended frequency of assessments, the methods used to determine the value for each characteristic and the way in which the data is presented to and utilised by the growers. Data is usually converted to soil maps which are then layered (where required) and interpreted via commercial software such as the Precision Decisions commercial platform, Mifarm. Access to Mifarm was provided, which allowed access to the commercial view of data collected.

3.5.2. Testing electroconductivity scans and soil sampling for prediction of slug patch location in field crops

Commercial EC scans (in lieu of soil texture) conducted by Precision Decisions at four field sites distributed between major cereal/OSR/potato growing regions of the UK (Tibberton, Adeney, Bridgnorth (Shropshire) and Billinghay (Lincolnshire)) were used in tests of the procedure for predicting slug patch location.

Scans of the whole of each field were taken, including an area in which a 1-hectare sampling grid had been marked out. Slug distribution within the grid was established using the standard sampling approach defined in section 3.2.1, and distribution maps were produced using the method described in section 3.2.3 and Forbes *et al.* (2021). The maps were then compared with the results of the soil scans. The EC scans were also uploaded to the Mifarm platform, by Precision Decisions, to demonstrate the various methods farmers could use to visualise the results

The commercial approach to collection of soil samples for pH and organic matter analysis was also adopted at the experimental sites, with the techniques described in section 3.2.2 used in laboratory analyses. Distribution maps of the two soil characteristics were then produced and compared with slug distributions. The scale of sampling ensured that soil was collected from within one metre of traps set in either patches with higher slug density, or interpatch areas. Thus, the data enabled the statistical models to compare spatial variation of soil characteristics and slug numbers accurately.

3.6. Integration into a practical system

3.6.1. Integration of project outcomes into a commercially viable targeted treatment approach

To support the integration of the various components developed in this project and previous (principally AHDB project no. 2140009118) studies into a procedure for patch treatment of slugs in commercial fields (WP6), mathematical modelling techniques were used to revisit a standard decision-making protocol for pesticide application based on the AHDB slug thresholds, which requires sampling using surface refuge traps and application of an action threshold when a mean catch of 4≤ slugs per trap is encountered. Previous work on targeted treatment of pest populations has centred on the feasibility of utilizing the strongly heterogeneous (patchy) spatial distribution of slugs within arable fields to treat only the areas of higher slug density, leaving intervening areas untreated (Forbes *et al*, 2017, 2020, 2021). Experimental protocol modifications were introduced to account for the potential application of pesticide only to selected spatial sub-domains, quantifying the minimum savings in area treated and the applicability of the standard AHDB action threshold within a patch treatment scenario.

Using field data collected using the method described in Section 3.2.1, an experimental mathematical approach to incorporating targeted application of pesticide into a control protocol that makes treatment decisions based on a threshold population was developed. The approach was designed to explore the impact of patch treatment on the level of suppression of the slug population in each field, and thus to consider whether the existing action threshold remains appropriate under scenarios where only part of a widely distributed population across a field is controlled, or whether a lower threshold is required to maintain effective pest management. Secondly, it was recognised that accurate patch location requires a clear recognition of what constitutes the patch edge before the location of the edge can be defined. A mathematical treatment of the available datasets was developed to explore this issue, which facilitated the accurate calculation of the area treated under a patch treatment approach, and thus the proportion of the field remaining untreated/saving in pesticide usage.

The mathematical progression developed during this aspect of the project requires lengthy description/consideration, and a full description has been published in Petrovskaya *et al*. (2020). Accordingly, only an outline description is provided in this report and the reader is referred to the 2020 paper for full details.

Soil Assessment approaches to identify patch location (include methodology and resolution)

3.6.2. Prototype procedure for the patch treatment of slug populations with control agents in commercial arable fields

In close consultation with industry representatives, the detailed findings of AHDB project no. 2140009118 and the current work (Ellis *et al*., 2020; Forbes, 2019; Forbes *et al*., 2017, 2020, 2021; Petrovskaya *et al*., 2018, 2020) were integrated to form a prototype patch treatment approach (WP6). Central to the approach developed was improved environmental and agricultural sustainability of slug control in UK crops, and encompassed constraints imposed by commercial viability and practicality identified by industry contacts.

3.6.3. Principle costs and cost-sharing

Utilising the outcomes of work conducted under sections 3.6.1 – 3.6.2, the principle costs to farmers of using the procedure developed in commercial practice in the major wheat/oilseed rape growing regions of the country were identified and discussed (WP6). Using winter sown oilseed rape as a model crop, expected changes to a recent gross margin budget resulting from use of the new procedure were calculated.

4. Results

4.1. Consultation with industry

Detailed discussion with key commercial partners was ongoing throughout the project, focusing on reviewing the latest findings of the experimental work, design of the next components of the programme, and their integration with existing technology in the development of a new patch treatment procedure.

Five industry sectors with which the project needed to communicate were identified, including companies providing services in soil assessment (with associated mapping software), application technology (particularly precision pellet application), GPS manufacturers, agronomists, and farmers. In addition, the trade press and participation in presentations at industry events provided a valuable route for wider promulgation of information (and in many cases feedback) and attracted further interest and offers of assistance from industry partners. The consultation influenced all aspects of the project (Figure 4), ensuring the work was designed and supported by current techniques and could be utilised using current technology and the final procedure took advantage of opportunities offered by current husbandry activities.

4.1.1. Agronomists and farmers

Key to the success of the project was the development of close contact and exchange of information/comment with agronomists and farmers. The project relied on this sector to provide underpinning specialist knowledge essential to the design of a commercially viable procedure for patch location/treatment.

The representative stakeholder of the Agronomy industry was Certis UK. The company provided valuable insights into the requirements of and constraints faced by both the Agronomy sector and individual commercial farmers, initially through face-to-face meetings, and following the first Covid-19 lockdown via appropriate communication software. When doing this the company also offered to approach individual farmers on our behalf to locate field sites across the crop growing regions of the UK for experimental work. In addition, Certis facilitated and sponsored a meeting to discuss the work undertaken and potential commercial outcomes, involving themselves, project-related personnel (Walters; Forbes), independent slug biology experts and statisticians. The company also invited (and sponsored) the PI to give a seminar as part of their slug hub activities at CropTech 2019). The presentation, entitled “Environmentally sustainable and commercially viable control of slugs: Towards a new approach” attracted a significant audience, was well received, and generated an important discussion, and after the event stimulated follow-up contacts from a wide range of individuals from across the industry.

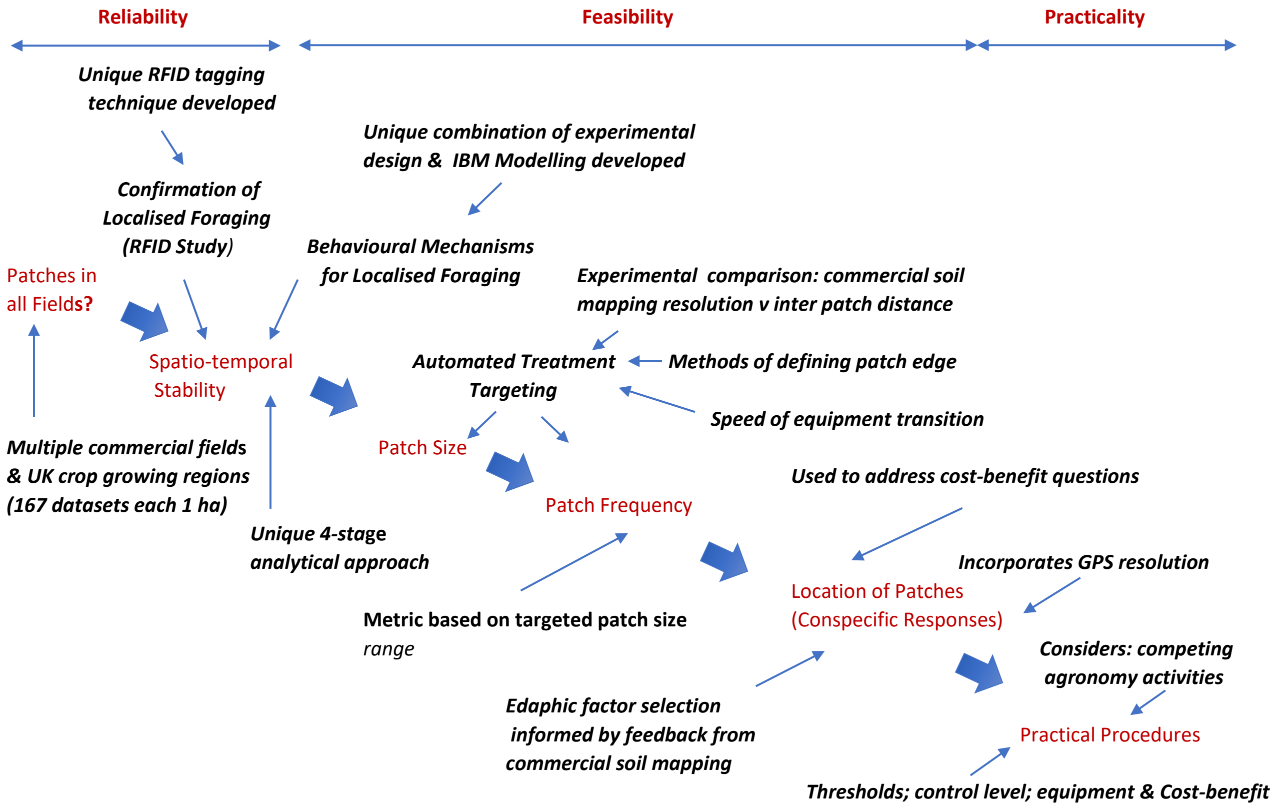


Figure 4. Examples of the impact of industry consultation on the approaches used during the delivery of the work programme, listed under the three main areas of concern (reliability, feasibility, practicality) identified by farmers/agronomists. Red font = Primary research areas addressed; Bold italics = Amendments to work plan in response to information/advice received.

Direct consultation with individual farmers initially utilised contacts developed under AHDB Project (no. 2140009118) to obtain field sites across major UK arable regions. These were supplemented by contacts made at open meetings, AHDB farm visits (1:1 or in small groups) crop walks, various industry events (e.g. CropTech, 2019; Cereals live 2020), and events which, collectively, facilitated discussions with growers of a range of relevant crops (oilseeds, cereals, salad growers, etc.). Project personell were also encouraged to actively contributed to selected industry events as listed in section 4.1.5 below.

Direct communication with a wider group of farmers/consultants (and other sectors) was achieved through the network established during AHDB project (no. 2140009118), and through the AHDB Monitor Farm Network which provided a valuable forum for additional knowledge exchange and feedback.

Feedback from farmers and agronomists could be divided between three main categories, feasibility of developing a commercially acceptable procedure within the constraints imposed by slug biology, reliability of the developing procedure, and practicality of the system (with particular emphasis on the potential for it to be integrated with wider farm activities and cost-benefit issues). As examples (not comprehensive) of issues raised by representatives of the sector:

Feasibility: Farmers were aware of the grid trapping used for experimental work and recognised it would be inappropriate on a field scale. Accordingly, all asked how the location of patches could be established using a commercially realistic approach?

Are the soil characteristics which will be used to determine the location of patches known?

Can they be used to identify slug patches with sufficient precision. For example, to guide the turning on and off of pellet application, will soil characteristics indicate where the patch edges are?

Dedicated soil assessments for patch location may prevent patch treatments being cost-effective, is it possible to use assessments already taken for other purposes for slug patch location?

Reliability: Do patches occur in all arable fields or simply in some fields (if the latter what proportion of the fields), and can their location be reliably established?

Does the spatio-temporal stability of the patches result in them always occurring in the same places throughout the window in which crop protection measures are used. If sufficient spatio-temporal stability is identified, could this be a feature of only the sub-set of fields in which experiments were conducted or are there factors of the slug biology that will make them stable in all fields?

How does the level of control achieved with patch treatment compare to treatment of a whole crop? Will comparative trials be run?

Practicality: Will the equipment already widely used on farms for slug pellet application have to be replaced or can it be modified for patch treatment?

As the proposal was to use soil maps generated from existing soil assessment approaches, can the existing mapping software be adapted or will bespoke software be needed?

Similarly, will existing GPS equipment be usable?

Does the range and frequency of patch sizes detected in commercial fields indicate that the saving in the amount of pesticide used to treat a hectare of crop using a patch treatment approach, when compared to treating the whole area, is sufficiently large to be cost-effective?

What level of control is achieved by patch treatments compared with whole-field treatment. Linked to this, there was a focus on the cost of soil assessments and the potential for sharing these costs with assessments used for other husbandry activities?

Integration into wider farm activities was frequently raised. For example, when during the growing season would soil assessments have to be taken; how stable are the soil characteristics used; how frequently will assessments need to be made (annually, biannually, etc.)?

Was there potential to conduct soil assessments during less intense periods of the growing season when other commitments allowed more time?

Would patch treatment require a new treatment threshold to be developed and tested or could the existing AHDB threshold be incorporated into the procedure?

4.1.2. Soil assessment and mapping software

The representative stakeholder consulted for the industry sector providing soil assessment services was Precision Decisions, a company offering a range of automated on-farm soil mapping services for the agricultural industry. Regular (at least monthly) discussions of a wide range of issues were arranged, initially via in-person meetings and later by Zoom or Teams, supplemented by field visits, a training workshop and direct observation of commercial soil assessment procedures.

Initially knowledge exchange focused on an explanation by the project team of the background of the work programme, current outcomes, and areas requiring further information. The project team sought and received advice and information on the soil characteristics that are currently mapped for commercial agriculture, providing a basis from which to determine the potential for, and possible approaches to, cost sharing between patch treatment and other on-farm activities. For example, soil characteristics commonly assessed commercially displayed a strong overlap with those being investigated by the project team as possible predictors of slug patch location (soil texture, organic matter. pH, bulk density and particle density), and informed the choice of the final sub-set incorporated into the prototype system.

Precision Decisions then developed the interaction by providing detailed information and discussions of soil sampling procedures and EC scanning machinery, culminating in a training workshop and subsequent in-field observation of use of the equipment in a commercial context. This provided critical support enabling integration of the technology into the developing patch treatment approaches. Data resolution (number of sample points per unit area) was found to be sufficiently large when compared with the density required to define the location of higher density slug patches within the size range previously shown to occur in arable fields (Forbes *et al*., 2021; AHDB Project (no. 2140009118). Information on the seasonal timing of assessments and frequency of re-sampling informed both the design and interpretation of work describing the temporal stability of the variation of soil characteristics across arable fields between cultivations (see below). Adding to these examples, training for current online systems/transferability of mapping software was also provided together with advice on interpretations of soil scans. A range of other information on a wide variety of topics relevant to the project was also provided.

Practical assistance was offered as required including, again as examples, introductions to industry contacts, identification of potential field sites to increase the geographical range of sites already used for field work, bespoke soil mapping of experimental fields/rotations using standard commercial equipment/procedures and a range of other support.

Constraints imposed by the Covid-19 pandemic severely limited the ability of the project team to travel to and conduct time-series sampling of soil characteristics in fields from all crop growing regions of the country, jeopardizing delivery of the research into temporal stability of critical characteristics. To address this problem Precision Decisions provided anonymized historic soil maps from commercial fields, which had been taken over a period of up to five years, allowing the impact of cultivations to be assessed (see below). This was a critical intervention without which it would not have been possible to complete the work of the project.

An approach by, and subsequent discussion with, another company (Hutchinsons Ltd.) towards the end of the project indicated that alternative soil assessment technology may also be compatible with the patch treatment procedures under investigation. The TerraMap/Omnia system, uses passive gamma-ray detection technology to produce high-definition (more than 800 reference points per hectare) mapping layers of an appropriate range of soil properties (soil texture, organic matter, pH). Naturally emitted isotopes such as Caesium and Potassium are measured, and outcomes are not adversely affected by cultivation state, compaction, or crop cover. This facilitates a wide operating window, allowing soil assessments for patch location to be addressed at commercially convenient points of the cropping cycle, and supports the potential for data collected for other agronomic purposes to be re-used, thus enhancing cost-effectiveness.

4.1.3. Application technology

To ensure that the approach to patch treatments developed under the project reflected the capabilities of current application technology, contacts from companies manufacturing pelleters and spraying equipment (the latter for potential future use of biological control agents) were consulted wherever required. The representative stakeholder was Stocks Ag. With wider consultation involving John Deere with individual conversations with other suppliers at industry events as opportunities arose. Discussions were usually conducted via Zoom or Teams meetings, or by email.

The most commonly used application method for slug pellets involved specially developed small spreading machinery with a spinning disc, although spinning disc fertiliser spreaders fitted with a small particle restriction kit can also be used. Both types ensure an even spread by overlapping adjacent spread widths. Applicators should ideally be capable of being fitted to a range of vehicle types including ATV’s, UTV’s, tractors, self-propelled and trailed sprayers, and cultivation machinery. Spread width is standard, for example StocksAg market a fan jet applicator that can be fitted to all of the above machinery types, which applies slug pellets to a 24m spread width. Variation between machinery was noted, e.g. some had a manual on/off for application, and mounting variable rate pelleters on quad bikes can be weight dependent.

Slug patches are irregular in shape. Assuming a standard spread width, and a treatment involving parallel passes across the field spaced at regular intervals along the field edge, targeting of treatments can be achieved by switching pellet application on at the first encounter (at any point along the spread width) with the “leading edge” of the patch, and off when losing contact with the trailing edge. This results in a rectangular area being treated that contains the slug patch.

The degree of accuracy by which patch edges can be targeted depends in part on the speed at which pellet application can be switched on and off, and discussion of this aspect established that it can be incorporated into a practical system by adding a small “buffer area” in advance of the patch edge to allow for the machinery to be delivering pellets at the required rate by the time the real edge is encountered.

The area treated using this approach can be readily calculated, allowing the proportional saving in the amount of slug pellets applied to a crop when patch treatment is compared with broadcast treatments to whole fields to be readily calculated (see sections 4.6.1 below).

It was concluded that patch treatment can be undertaken using existing equipment without the need to invest in expensive new machinery.

4.1.4. GPS manufacturer/Pelleter manufacturer

Conclusions of earlier work under AHDB Project (no. 2140009118) indicated that establishing patch location using assessments of slug surface activity would be both insufficiently accurate and too labour intensive, necessitating an alternative automated approach to be developed. Under the current project a technique by which variability of defined soil characteristics across a field is used to determine where patches will be located was investigated. Industry consultation regarding assessment of soil characteristics and production of soil maps from the data collected is addressed in section 4.1.2 above. It was proposed that maps of the variability of edaphic factors across arable fields could be used to define when the edges of slug patches will be encountered as the pellet applicator is driven across the field. However, for practical use it is necessary to relate the soil map to the precise location of the applicator in the field and its direction of movement.

Advice was sought from GPS Manufacturer, Patchwork Technology, largely through direct correspondence and telephone conversations, supplemented by inter-segment communication with companies detailed in sections 4.1.2 and 4.1.3. It was established that GPS can operate in conjunction with maps produced by the software developed and used by Precision Decisions to define when slug pellet applications should be turned on and off. Consultation with the stakeholder representative (primarily Stocks Ag. and John Deere) for application equipment manufacturers confirmed that the GPS systems available are also compatible with most standard pelleters.

4.1.5. Trade press/, industry events and AHDB Monitor Farm network

Invitations to speak were accepted from a range of events, including the Crop Protection Association annual general meeting (Environmentally sustainable and commercially viable control of slugs); CropTech (see above for details); AAB Advances in Biocontrol and IPM Conference (The grey field slug: A challenge for sustainable pest management in the UK); and BCPC Pests and Beneficials Review 2021 (Industry liaison: A key driver of IPM solutions). Where the event was live, the opportunity was taken to discuss the proposed patch treatment procedure with individuals manning relevant industry stands. During the previous AHDB funded project, presentations at monitor farm events and discussion with the attendees provided an industry feedback mechanism. Due to COVID19 restrictions, the planned attendance at these events was not possible. A presentation and project discussion with stakeholders were given, however, at the AHDB Regional Agronomy meeting (NW) early in the project, prior to COVID restrictions.

Further promulgation of the findings by the trade press stimulated wider discussion and advice. During the life of the current project, a series of independent journalists, most of whom had previously reported our work, requested further interviews and support for writing follow-on articles to update readers on progress made. In one case an accurate article was written without reference to us, with information probably drawn from published papers and presentations delivered by project participants. During the current project, requests from journalists developed their own momentum and other than two arranged by AHDB required little or no stimulus from project staff. Supporting interviews were conducted entirely by email, Zoom or Skype. As examples, articles published in 2020 included, amongst others:

Anonymous (2020). Grey field slug research aims to reduce pesticide use. In: *International Pest Research*
Blake, A (2020).Patch precision aims to improve slug control. In: *Arable Farming*.
Pasture, De La., L (2020). Full field treatments, a sledgehammer to crack a nut*? CPM*.
Gunn, S. (2020). Cost effective and environmentally sustainable a new approach to slug control.

4.2. Development of a procedure for predicting locations in which slug patches will develop

4.2.1. The effect of soil structure, organic matter, soil pH on the location of patches of higher slug density in arable fields

The fields assessed in the 2019-20 field season reflected a large proportion of the normal range of the data values recorded in arable fields in the UK for each of the edaphic factors assessed (Table 2). The range of soil types investigated included sandy loam, clay loam and sandy clay loam.

Soil pH covered the range 4.37 – 7.90, which accounts for all but the extreme soil pH’s found in arable soils in the UK.

Table 2. The results of slug counts and analysis of soil samples taken in eight fields during 2019/20 field season. Between 3-5 slug counts were taken in each field between November 2019 and March 2020, using a 10x10 grid of surface refuge traps with 10 m between nearest neighbours thus covering an area of 1 h. A total of 30 soil samples were collected from each grid in either February or March 2020.

County	Location (No. Slug counts)	previous crop	crop	Bulk density g/cm^3 range (mean)	pH range (mean)	Organic matter % range (mean)	Particle density g/cm^3 range (mean)	Sand % range (mean)	Silt % range (mean)	Clay % range (mean)	Mean No. slugs per trap
Shropshire	Ludlow (4)	winter barley	OSR	1.0 - 1.3 (1.2)	4.37 - 6.15 (5.2)	4.4 - 8.4 (5.9)	2.02 - 2.69 (2.3)	46.6 - 55.0 (50.5)	26.3 - 36.2 (31.1)	15.9 - 21.4 (18.5)	5.66
Shropshire	Tibberton (5)	OSR	Wheat	0.9 - 1.3 (1.1)	5.13 - 6.88 (5.9)	5.5 - 8.2 (6.7)	1.77 - 2.10 (2.0)	45.7 - 55.6 (50.9)	18.1 - 22.7 (20.5)	25.3 - 32.2 (28.6)	2.73
Cheshire	Widnes (4)	OSR	Wheat	1.3 - 1.6 (1.4)	4.49 - 6.03 (5.2)	4.2 - 7.5 (5.3)	0.72 - 2.41 (2.2)	44.5 - 60.3 (55.6)	20.1 - 27.8 (23.1)	18.7 - 27.8 (21.3)	0.94
Lincolnshire	Billinghay (5)	Wheat	OSR	0.8 - 1.3 (1.1)	5.03 - 7.13 (6.4)	6.4 - 13.4 (9.5)	1.35 - 2.30 (1.9)	39.1 - 44.4 (42.1)	24.2 - 37.5 (31.9)	19.6 - 34.6 (26.0)	3.53
Lincolnshire	Fulletby (5)	OSR	Wheat	0.8 - 1.2 (1.0)	7.51 - 7.90 (7.7)	6.6 - 8.8 (7.3)	1.89 - 2.20 (2.0)	38.2 - 50.5 (43.5)	21.4 - 32.2 (27.4)	27.5 - 32.9 (29.2)	0.40
Yorkshire	Beverley (3)	Wheat	OSR	1.2 - 1.6 (1.3)	4.95 - 6.09 (5.7)	4.2 - 6.2 (4.9)	1.97 - 2.41 (2.1)	37.4 - 49.1 (45.5)	28.7 - 39.9 (32.3)	17.8 - 25.8 (18.9)	4.58
Yorkshire	Shipton (3)	Wheat	OSR	1.0 - 1.4 (1.2)	4.61 - 5.76 (5.1)	3.3 - 5.8 (4.3)	1.02 - 2.41 (2.1)	50.1 - 78.7 (58.8)	7.0 - 19.2 (11.9)	13.6 - 32.4 (19.3)	0.82
Wiltshire	Malmesbury (3)	Barley	OSR	n/a	6.08 - 7.42 (6.9)	6.8 - 8.7 (7.7)	1.96 - 2.28 (2.1)	45.6 - 51.7 (49.2)	21.0 - 28.6 (24.0)	23.6 - 29.5 (26.8)	0.60

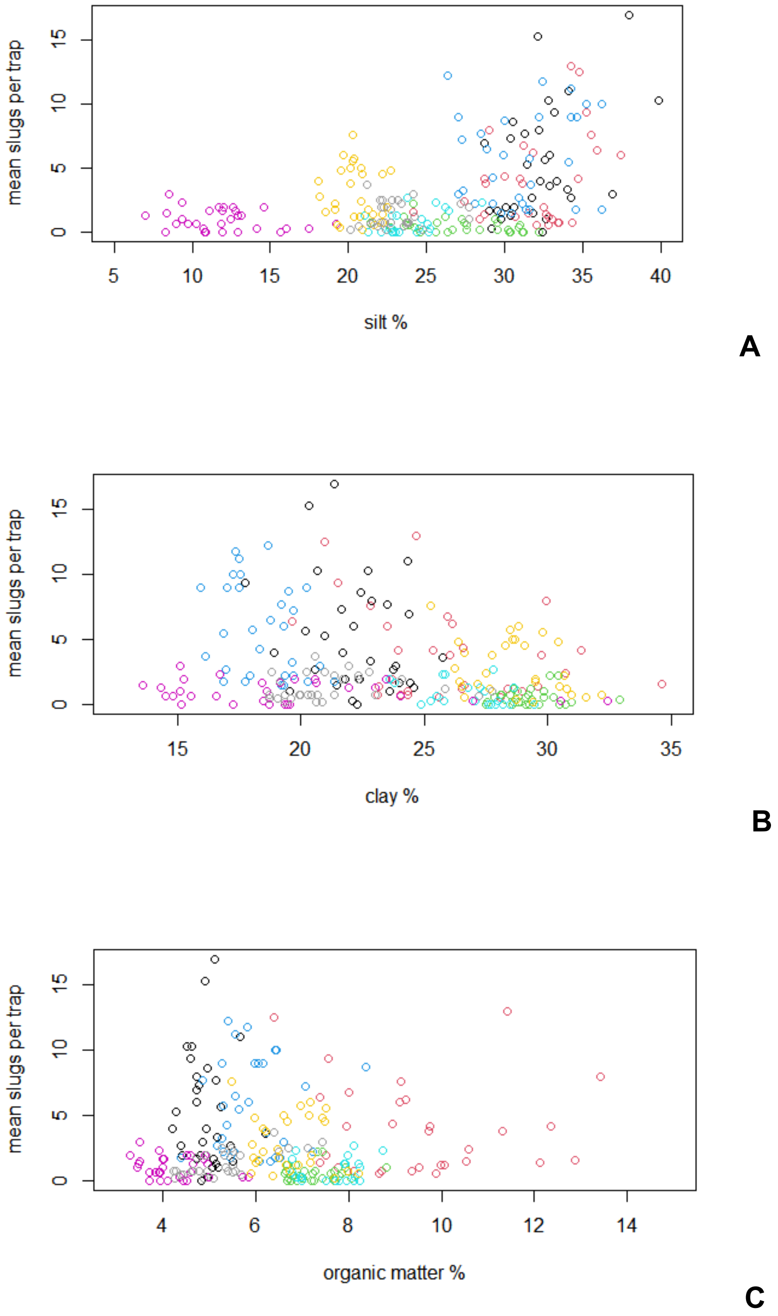


Figure 5. The relationship between mean number of slugs caught in refuge traps set in either patches of higher slug densities or interpatch areas and (A) the % silt content of soil adjacent to the trap; (B) %clay content of soil adjacent to the trap; (C) soil % organic matter content adjacent to the trap. Soil samples were taken from 30 locations in each of eight fields (in Shropshire, Cheshire, Yorkshire, Lincolnshire and Wiltshire). Colours represent different fields. Slug patch and interpatch areas were identified using the method of Forbes *et al*. (2021).

There was a significant relationship between the mean number of slugs recorded in surface refuge traps and soil texture (Figure 5a and b: log(silt) $z = 2.5$, d.f. = 226, $p < 0.01$; log(clay) $z = -4.5$, d.f. = 226, $p < 0.001$ respectively). Similarly, mean slug numbers in traps were significantly related to organic matter content of the soil (Figure 5c: $z = 2.8$, d.f. = 226, $p < 0.01$). Bulk density, particle density and pH were not found to have a significant effect on the number of slugs per trap (Bulk density $z = -0.1$, d.f. = 200, $p > 0.05$; particle density $z = 0.5$, d.f.= 200, $p >0.05$; pH $z = -1.1$, d.f.=200, $p>0.05$).

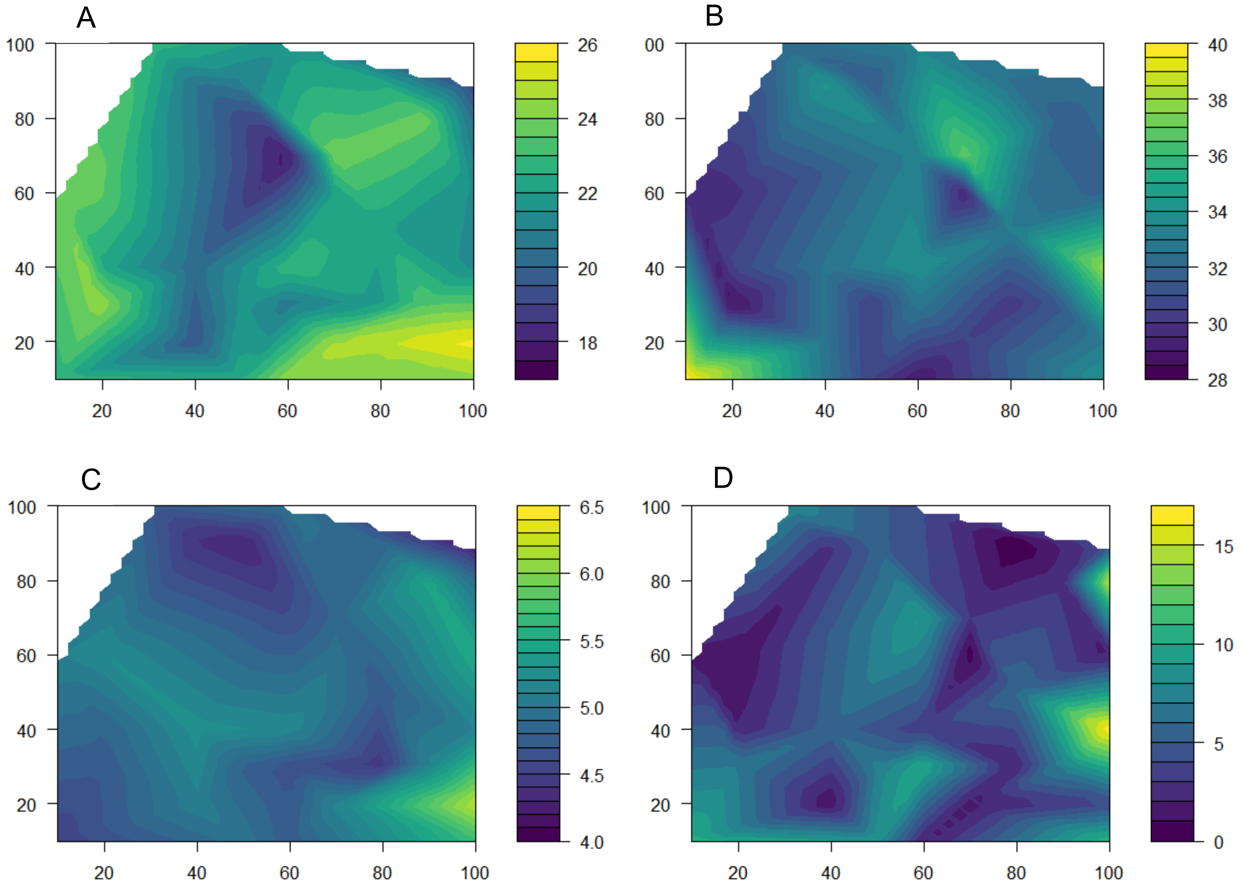


Figure 6. Variation of edaphic factors, (A) clay (B) silt and (C) organic matter, and (D) mean number of slugs per trap, within a 100 m by 100 m grid in a field near Beverley, Yorkshire. Axis show distance between points in metres. Soil samples were taken from 30 points within the grid which had been identified as harbouring a consistently high or low number of slugs per trap. Colour scales represent the percentage of (A) clay, (B) silt and (C) organic matter and (D) number of slugs, the numbers between the sampling points were calculated by polynomial interpolation.

The impact of the variation in the levels of clay, silt and organic matter in soil on number of slugs caught in surface refuge traps is vizualised in the distribution maps for two fields (taken as examples) in Figures 6 and 7. Comparison of the maps indicate that although highly significant statistical relationships occur between slug activity and individual edaphic factors occur, slug distribution is the result of a complex interaction between all three factors, resulting no individual factor fully accounting for the variation in the number of slugs. Accordingly, the most accurate prediction of patch location is likely to be achieved a combination of soil factors, potentially including soil texture, and organic matter.

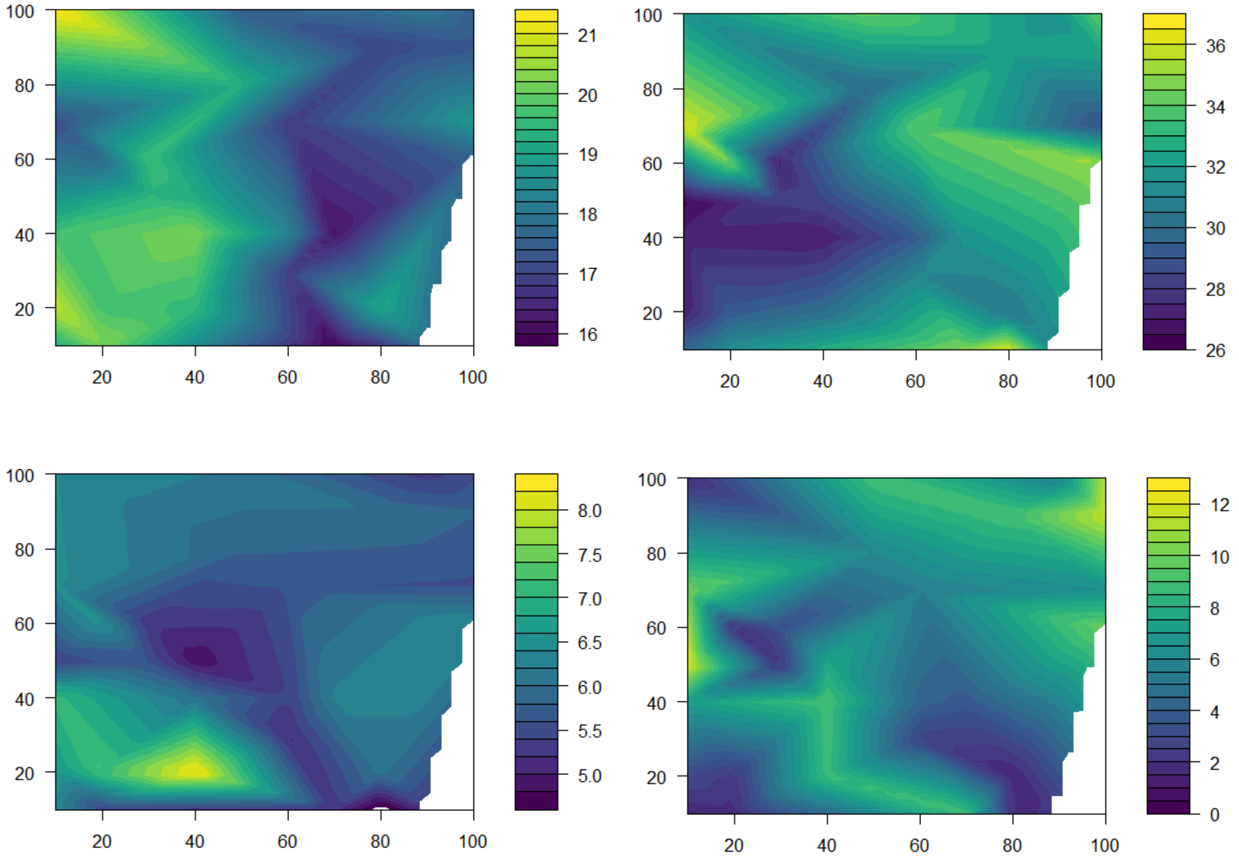


Figure 7. Variation of edaphic factors, (A) clay (B) silt and (C) organic matter, and (D) mean number of slugs per trap within a 100 m by 100 m grid in a field near Ludlow, Shropshire. Axis show distance between points in metres. Soil samples were taken from 30 points within the grid which had been identified as harbouring a consistently high or low number of slugs per trap. Colour scales represent the percentage of (A) clay, (B) silt and (C) organic matter and (D) number of slugs, the numbers between the sampling points were calculated by polynomial interpolation.

Using the same variables (percentage silt, clay and organic matter) the results of the logistic regression showed that clay and silt had a significant effect on the binary decision of whether to apply slug pellets to patches or to leave them untreated (log(clay) z = -2.3, d.f. = 227, p = 0.02, log(silt) z = 2.0, d.f. = 227, p = 0.049). Organic matter did not show a significant effect on the decision to apply pellets (z = 1.7, d.f. = 227, p = 0.09).

4.3. Testing the procedure for predicting slug patch location in major arable regions

4.3.1. Using soil characteristics to predict areas with higher slug numbers slug numbers

Of the ten fields surveyed in the 2020-21 field season, three were found to have slug numbers sufficiently high to support the planned analysis (Table 3). The range of data-values for soil texture, organic matter content and soil pH in the three fields studied differed from those recorded in the set of fields used to establish the relationships with slug patch location in the 2019-2020 field season. The range of pH in the samples from the 2020-21 season was slightly lower than in the previous year, (4.22 - 7.05 in 2020-21 compared to 4.37 - 7.90 in 2019-20). The range of organic matter content was also narrower (4.1 - 8.9 compared to 3.3 – 13.4 percent in 2019-20). In contrast, the soil texture results from the fields sampled in 2020-21 were broader than the previous year, with a wider range of sand, silt and clay observed. In 2019-20, sand 37.4 – 78.7%, silt 7 – 39.9 % clay 13.6 – 34.6%; in 2020-21, sand 1.7 – 83.4, silt 5.3 – 68.8, clay 6.6 – 54.2 %

Results of analysis using the negative binomial mixed effects model for the 2020-21 samples, showed organic matter ($z = 2.4$, d.f. = 54, $p < 0.05$) and soil texture (log(clay) $z = 2.3$, d.f. = 54, $p < 0.02$; log(sand) $z = 3.2$, d.f.= 54, $p < 0.001$) to have a significant effect on the relative number of slugs per trap, confirming the results of work carried out under this project during the 2019-20 season.

Edaphic characteristics are only a subset of the factors affecting the number of slugs that are active on the soil surface. Thus as expected, the negative binomial mixed effects model developed using data collected in the 2019-20 field season (section 4.2.1) to estimate the actual number of slugs at each point using the selected soil factors, showed no significant relationship between observed and estimated catches in surface refuge traps ($F = 2.1$, d.f. = 1, 78, $p = 0.16$). However, the logistic regression mixed effects model (see section 4.2.1) developed to predict the relative number of slugs present in different *areas* of the field (i.e. slug patch location) showed an 81% accuracy in predicting whether a sampling point exceeded the presumptive 4/trap level using the test set of data generated from the 2019-20 results. When the new data from the 2020-21 season was input into the model, however, the accuracy of allocating sampling points between the two categories of greater or less than the presumptive level of 4 slugs/trap was reduced to 40%. Of the incorrect allocations only 18% were false negatives, which would have resulted in failure to apply control treatments.

The outcome in 2019-20 was affected in part by a high level of successful predictions in the four fields with higher numbers of surface active slugs (mean catches per trap of 2.73; 3.53; 4.85;

5.66; Table 2). These population levels were generally much larger than those in the three fields investigated in 2020/21 (mean catches of 1.8, 2.8 and 2.85 per trap; Table 3). It has been established that accurate identification of slug patches using surface refuge traps is very difficult when the number of surface-active slugs is low (Forbes *et al*., 2021), thus the apparent lower success in predicting slug patch location using the model in 2020/21 may have been significantly affected by limitations of the trapping method used, that resulted in less accurate experimental identification of the patches of higher slug densities themselves.

4.3.2. Testing the patch treatment approach on an AHDB strategic farm

Due to the limited opportunity to screen field sites prior to establishing the experiment, very low slug populations were detected in the initial assessments, but catches were similar in both trapping grids. For assessments taken on 12 October 2020, the total number of slugs recorded in Grid 1 (uniform application of pellets) was 26 compared to 31 in Grid 2 (targeted pellet application); in assessments taken on 14 October a total of 13 and 19 slugs were recorded in Grids 1 and 2 respectively. Differences in trap catches between the two sampling dates reflect the effect of prevailing weather on the day of assessment on the surface activity of slugs. Within each sampling day, slug populations were similar across the two grids, thus there were comparable baseline populations prior to the application of slug pellets.

Within the grid with slightly higher trap catches (Grid 2), slug distribution maps were created following the initial trap counts (Figure 8) and used to identify patches with significantly higher slug numbers. In order to ensure any applications to the grids were commercially realistic the same pellets were used (Sluxx, Certis, UK) as the farmer was applying to the surrounding crop and the timing of application to the grids was within 5 days of the commercial application. Treatments resulted in 30% of the total grid area receiving a slug pellet treatment, compared to a uniform application to the whole (100%) of Grid 1 to reflect normal farm practice (both grids treated on 16 October).

Table 3. The results of soil analysis and slug counts in ten fields sampled during the 2020-21 field season. Sampling points (20 per field) were dispersed across the field to include areas of higher and lower electroconductivity, based on EC scans conducted using commercial procedures and machinery by Precision Decisions Ltd. Soil samples were collected in September and October 2020. Slug numbers were assessed using refuge traps, 2-3 assessments were carried out per field during February and March

County	Location	previous crop	crop	Bulk density g/cm^3 range (mean)	pH range (mean)	Organic matter % range (mean)	Sand % range (mean)	Silt % range (mean)	Clay % range (mean)	No. slugs per trap	Use in further analysis
Shropshire	Adeney	Fallow	OSR	1.0 - 1.4 (1.2)	5.96 - 6.92 (6.5)	6.7 - 6.8 (5.1)	46.3 - 75.5 (58.6)	12.9 - 21.3 (18.6)	11.1 - 37.0 (22.9)	1.20	NO
Shropshire	Ludlow (1)	OSR	Wheat	0.9 - 1.3 (1.0)	4.89 - 5.87 (5.3)	1.2 - 8.9 (6.5)	20.5 - 51.7 (36.2)	31.9 - 53.6 (44.0)	13.1 - 29.0 (19.8)	1.80	YES
Shropshire	Ludlow (2)	Wheat	OSR	1.0 - 1.4 (1.2)	4.70 - 6.46 (5.5)	4.2 - 6.2 (5.2)	17.8 - 56.0 (39.5)	31.3 - 57.4 (43.4)	12.7 - 24.8 (17.1)	0.60	NO
Shropshire	Ditton Priors	Wheat	Wheat	0.9 - 1.3 (1.1)	5.67 - 6.61 (6.2)	3.8 - 7.8 (5.6)	10.1 - 41.5 (25.7)	38.7 - 68.8 (53.3)	14.8 - 33.1 (21.0)	0.50	NO
Cheshire	Widnes	Spring beans	Wheat	1.0 - 1.3 (1.2)	4.22 - 7.05 (5.1)	5.1 - 8.9 (6.3)	56.8 - 71.2 (61.8)	9.5 - 17.3 (13.3)	14.7 - 28.9 (25.0)	2.80	YES
Lincolnshire	Billinghay	OSR	Wheat	0.7 - 1.3 (0.9)	6.20 - 7.69 (7.2)	9.4 - 18.0 (13.6)	1.7 - 10.0 (3.7)	44.0 - 64.1 (54.7)	29.7 - 54.2 (41.6)	0.20	NO
Yorkshire	Shipton	Spring beans	Wheat	0.8 - 1.4 (1.2)	5.56 - 7.47 (6.4)	4.1 - 6.4 (5.4)	42.9 - 83.4 (66.3)	5.3 - 23.3 (15.7)	9.2 - 33.9 (18.0)	2.85	YES
Yorkshire	Beverley	Wheat	Barley	0.9 - 1.3 (1.1)	4.84 - 7.84 (5.9)	3.9 - 9.2 (5.7)	37.3 - 64.4 (52.9)	26.7 - 34.7 (31.1)	6.6 - 28.2 (16.0)	0.35	No
Suffolk	Bury St. Edmonds	Linseed	Wheat	1.2 - 1.5 (1.4)	6.04 - 8.07 (7.7)	4.3 - 5.9 (5.0)	37.2 - 62.6 (48.1)	17.4 - 31.6 (27.3)	18.5 - 31.7 (27.3)	0.40	NO
Cambridgeshire	Wisbech	Wheat	Wheat	1.1 - 1.4 (1.3)	6.29 - 9.70 (7.3)	4.9 - 6.7 (5.9)	7.5 - 29.3 (15.8)	50.0 - 68.5 (59.0)	13.0 - 35.1 (25.2)	0.03	NO

Two further assessments of slug numbers were carried out 4 and 17 days after application, with a total of 15 and 3 slugs respectively recorded in the 100 traps set in Grid 1. Trap catches of 15 and 8 were recorded in Grid 2 respectively at the 4 and 17-day post-treatment application sampling visit. In the grid receiving the broadcast treatment of slug pellets across the whole 1 ha plot (Grid 1), this equates to an 88% reduction in the catches of slugs by the final post-treatment assessment (when compared with the higher of the two pre-treatment assessments). In Grid 2, in which pellets were targeted only at slug patches (30% of the total area), a population depression of 74% was recorded, similar (i.e. within sampling error for this population size) to that in the broadcast treatment. The number of dead slugs showing signs of consumption of slug pellets were identical (4) in both grids in the first assessment after application, data for mortality counts at day 17 could not be interpreted due to partial or complete decomposition of a proportion of the molluscs. Thus, within the limitations imposed by the low slug populations at the experimental site, no differences in the level of control achieved by broadcast or patch targeted treatments of slug pellets were found.

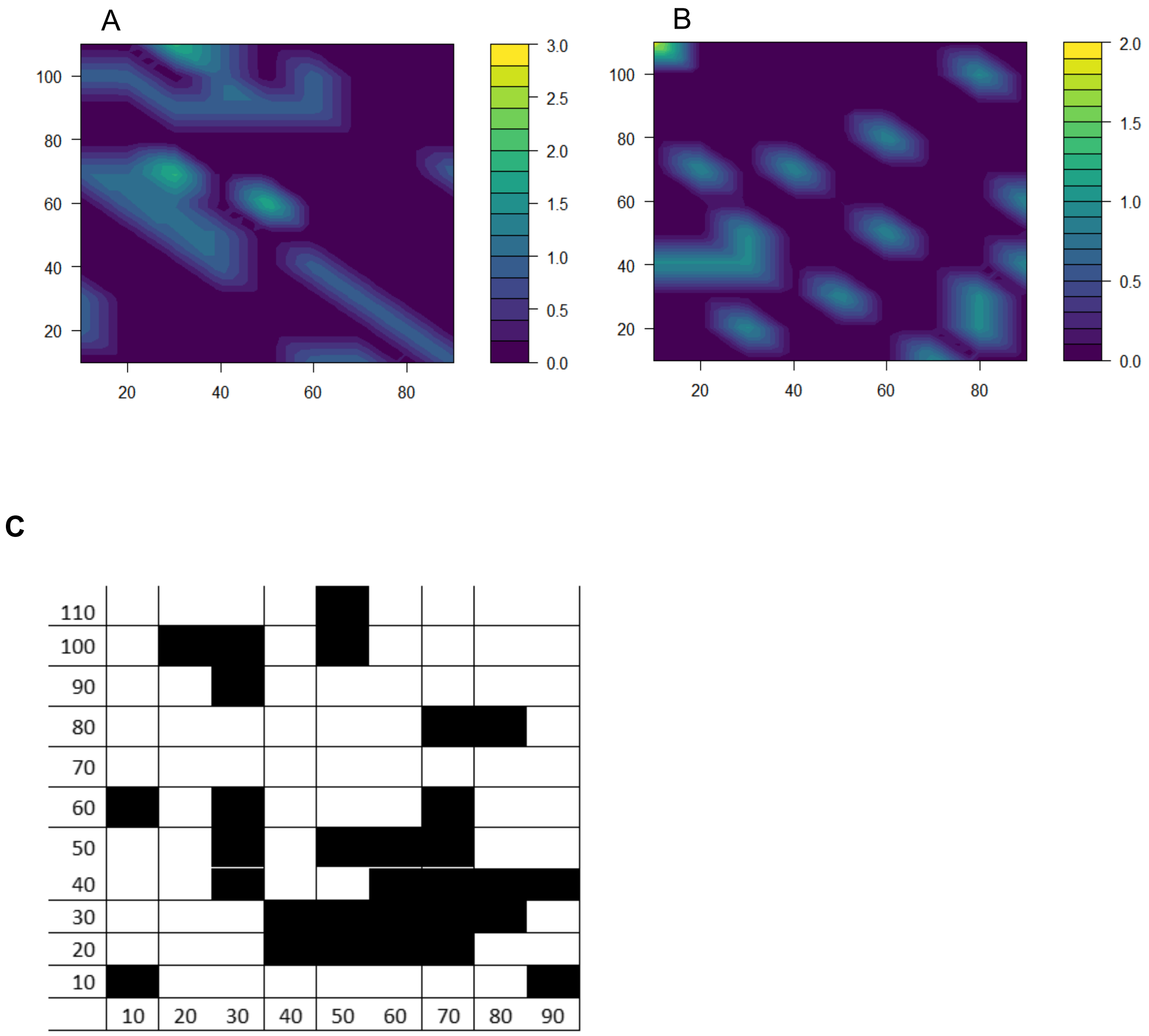


Figure 8. Slug distributions within a 100 m by 100 m grid in a field on the AHDB Strategic Farm West, near Leamington Spa, Warwickshire on (A) 12/10/20 and (B) 14/10/20, and (C) the areas of the field that were treated. Axis show distance between points in metres. Colour scales represent the number of slugs per trap, the numbers between sampling points were calculated by polynomial interpolation.

4.4. Testing soil characteristic and slug patch stability

4.4.1. Spatio-temporal stability of soil characteristics

Analysis of historical data from designed experiments – Soil pH and organic matter content

Soil pH in the two fields in Shropshire and Leicestershire that were studied for two consecutive years (2016 and 2017) in AHDB project (no. 2140009118), displayed a high degree of stability between seasons. There was a significant correlation between the pH of soil taken from the same nodes in the sampling grids in both the Shropshire field ($r = 0.51$, $t = 5.65$, df = 90, $p < 0.001$), and the Leicestershire field ($r = 0.44$, $t = 4.79$, df = 94, value <0.001).

Results of the study of soil organic matter content were less definitive. Data from the previous project showed a significant correlation between points in two consecutive years (2016 and 2017) in the Shropshire field ($r = 0.75$, $t = 11.0$, df = 95, $p < 0.001$), however, there was no significant correlation between points in the field in Leicestershire ($r = 0.19$, $t = 1.9$, df = 93, $p = 0.06$). The use of cover crops in the Leicestershire field may be a contributing factor to the differences observed. The addition of organic matter in the form of crop residue incorporation between growing seasons when cover crops are ploughed back into the soil, can affect the organic matter content of the soil.

Analysis of commercial field scans – Soil texture and soil pH

The results of electroconductivity scans carried out by Precision Decisions in the same arable field in 2009 and 2017, were provided for use in the project. Comparison of soil maps produced from the data (Figure 9), showed that although the absolute data points varied between the two assessments, suggesting gradual drift of some edaphic characteristics, the underlying patterns of higher or lower readings across the field remain stable.

Precision Decisions provided additional data on the distribution of soil pH across a field in Yorkshire which was sampled in 2011, 2015 and 2019. There were significant correlations between the recorded spatial variability of soil pH between all three combinations of dates (2011-2015: $r = 0.82$, $t = 7.1$, df = 25, $p < 0.001$; 2015-2019: $r = 0.79$, $t = 6.5$, df = 25, $p < 0.001$; 2011-2019: $r = 0.74$, $t = 6.5$, df = 36, $p < 0.001$). This result confirms the analysis of soil assessments taken in two adjacent cropping seasons from experimental fields studied in AHDB project no. 2140009118.

The consistency of pH values across multiple seasons in a range of fields suggests that this is a stable factor and that historic maps (by law a minimum of 5-yearly assessments are required) could be used to identify fields which fall outside of the range that allow slug populations to develop.

4.4.2. Spatio-temporal stability of slug patches

Hotspot analysis

The results of the field sampling and data analysis presented in this section have been published and full datasets for all 167 assessment visits are reported as supplementary materials provided with the paper (Forbes *et al.*, 2021).

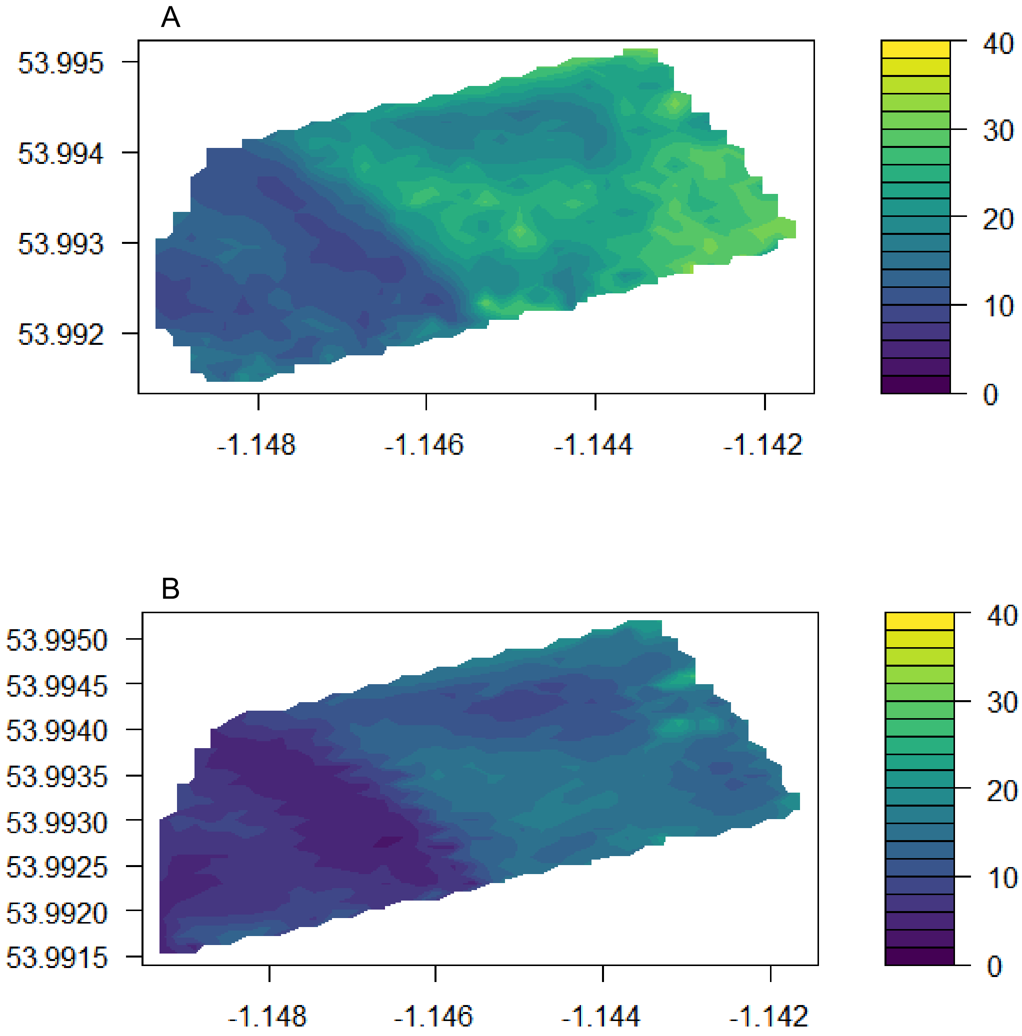


Figure 9. Electroconductivity scans conducted by Precision Decisions Ltd. in the same field near Shipton, Yorkshire, in two different growing seasons (A) 2009 and (B) 2017. X and Y axis show grid reference points. The colour represents the electroconductivity values.

Following confirmation of the aggregated distribution of slugs within the 1 ha plots in study fields established in an earlier study (established using Taylor's Power Law; Forbes, 2019), the location of discrete domains with significantly (P<0.05) higher numbers of slugs than would be expected if a random distribution is assumed, were identified using hotspot analysis and visualized using grid maps (Table 4; Figure 10).

Higher density domains were detected in either the majority, or all of the assessment visits to each of the 22 individual field crops investigated over the three years of this study (Table 4). Of the total of 167 assessment visits to these sites, higher density domains were recorded in 162 visits, with no such domains identified in only 5 assessments. These five visits coincided with periods of very low slug activity on the soil surface as recorded by refuge traps (Maximum = a mean of 0.07 slugs per trap). The lack of an effect of geographical location of the field on spatial distribution of slugs was evident, with significant heterogenous distributions recorded in 98.4% of the 129 sampling visits made to fields in the Western half of England, and 92.1% (of 38) in the dryer East.

Spatial stability of patches

The results of the data analysis presented in this section have been published and full details of statistical outputs are provided in the supplementary materials provided with the paper (Forbes *et al.*, 2021).

Table 4. The number of assessment visits to each field in which hot spot analysis identified discrete domains containing significantly higher slug density (p<0.05; HD) when compared with that expected if the population was randomly distributed across the sampling grid. Assessments made using a 10 by 10 grid of refuge traps set within a rectangular 1ha plot.

County/Field	Season	HD Domain	No HD Domain	County/Field	Season	HD Domain	No HD Domain
Shropshire				**Leicestershire**			
Shrops 1	2015-16	7	0	Leic 1	2016-17	8	0
Shrops 2	2015-16	11	0	Leic 1	2017-18	5	0
Shrops 2	2016-17	8	1	Leic 2	2016-17	7	0
Shrops 2	2017-18	8	0	**Lancashire**			
Shrops 3	2015-16	7	0	Lancs 1	2016-17	10	0
Shrops 3	2016-17	5	0	Lancs 1	2017-18	4	1
Shrops 4	2015-16	13	0	**Lincolnshire**			
Shrops 4	2016-17	5	0	Lincs 1	2016-17	8	1
Shrops 5	2015-16	8	0	Lincs 2	2016-17	8	0
Shrops 5	2016-17	7	0	Lincs 3	2016-17	7	1
Shrops 6	2016-17	7	0	Lincs 4	2017-18	5	1
Shrops 7	2017-18	7	0	**Nottinghamshire**			
				Notts 1	2016-17	7	0

In 11 of the 22 crops studied, consistent differences between the catches of individual traps were detected, indicating potential spatial clustering of slug activity, and reflecting the higher density domains identified by hotspot analysis. These included all five fields assessed in 2015/16, 3 of the 12 sites in 2016/17, and 3 of the five sites in 2017/18 (Table 5). A characteristic common to 10 of the 11 fields in which a more homogenous distribution of slug catches was recorded was a low slug infestation in crops (mean <1.5 slugs per trap). This was reflected in a catch of >4 slugs (the current

AHDB treatment threshold in winter wheat and oilseed rape in the UK) not being recorded in any individual trap in these fields. The remaining field was located on land that was still in the recovery phase following reclamation from a former opencast mining site with associated significant soil disturbance.

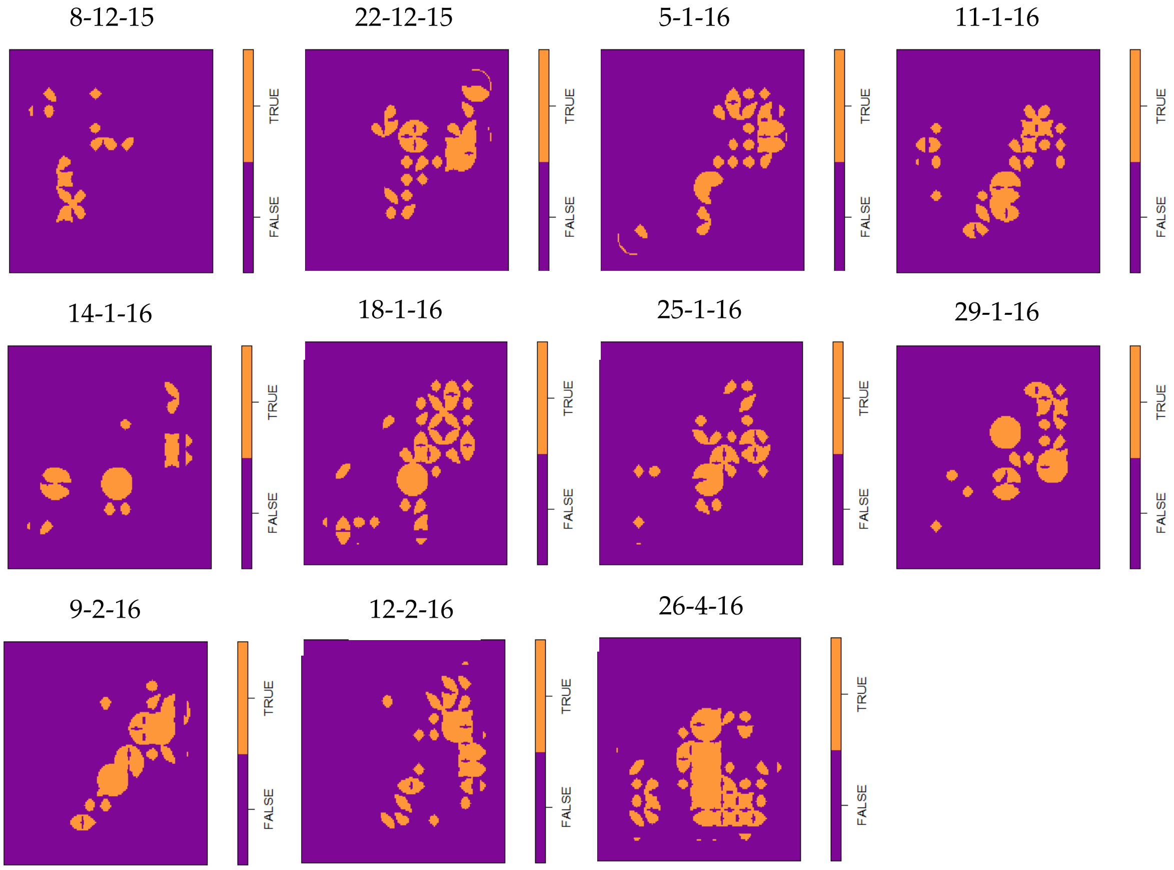


Figure 10. Visualized grid map showing the location of domains of higher slug density identified by hotspot analysis of data collected from a 10 x 10 grid of refuge traps, set within a rectangular 1ha plot at the Shrops 2 field site between December 2015 and April 2016. Data for each of the 11 assessments made at this site were analysed separately; grid squares coloured in amber indicate the location of discrete domains with significantly ($P<0.05$) higher numbers of slugs than would be expected if a random distribution is assumed. Dates above each map indicate the day on which the assessment was made. For grid maps from all field sites used in the study see supplementary materials in Forbes *et al*. (2021). The Shrops 2 field site was sampled in each of three consecutive growing cycles and for comparison equivalent grid maps for crops grown in the 2016/17 and 2017/18 cropping seasons are provided in Figures S1. (F) and S1. (R) in the supplementary materials provided in Forbes *et al*. (2021).

The grids of trapping nodes used in this study generated a data matrix describing the pattern of spatial clustering of slugs that are active on the soil surface on each assessment date. To investigate the degree of similarity between the location of the resultant slug patches defined by the data matrices collected on different assessment dates at the same site, the relationship between the numerical separations for all the possible pairs of trap samples taken on different dates was established using Mantel's permutation test (Mantel, 1967). The degree of correlation between the location of the slug patches in pairs of matrices from different sampling dates is a measure of spatial stability of the patches across the assessment period.

Table 5. Spatial clustering of slug activity identified by catches of surface refuge traps arranged in a 10 x 10 grid of refuge traps, set within a rectangular 1ha plot in each field, and mean number of slugs caught, in 22 field sites from three growing seasons. The effect of trap location within the grid on slug numbers was investigated using a Poisson GLM mixed effects model, with main effects extracted using the Anova function in R (X^2; p). Consistent differences between the catches of individual traps (indicating potential spatial clustering of slug activity) are highlighted in bold, and mean trap catches exceeding an arbitrary "low population size" of 1.5 per trap in bold/italics.

Site	Years	X^2	p	Mean trap count
Shrops 1	2015-16	136.50	**P <0.01**	0.7
Shrops 2	2015-16	82.31	**P <0.001**	***6.8***
Shrops 3	2015-16	136.16	**P <0.001**	***3.4***
Shrops 4	2015-16	14.69	**P <0.001**	***11.4***
Shrops 5	2015-16	18.20	**P <0.001**	***3.7***
Lancs 1	2016-17	157.70	**P <0.001**	***2.1***
Shrops 2	2016-17	11.47	**P <0.001**	0.1
Shrops 3	2016-17	0.05	P >0.05	0.1
Shrops 4	2016-17	0.30	P >0.05	0.2
Shrops 5	2016-17	20.99	**P <0.001**	***1.9***
Shrops 6	2016-17	1.35	P >0.05	0.4
Leic 1	2016-17	0.01	P >0.05	0.6
Leic 2	2016-17	0.09	P >0.05	1.2
Lincs 1	2016-17	1.88	P >0.05	0.5
Lincs 2	2016-17	2.08	P >0.05	0.2
Lincs 3	2016-17	0.92	P >0.05	0.1
Notts 1	2016-17	0.02	P >0.05	0.05
Lancs 1	2017-18	0.01	P >0.05	***2.1***
Shrops 2	2017-18	14.01	**P <0.001**	0.1
Shrops 7	2017-18	6.03	**P <0.05**	***3.4***
Leic 1	2017-18	2.24	P >0.05	0.3
Lincs 4	2017-18	6.79	**P <0.01**	***1.0***

Comparisons were made of all permutations of pairs of data matrices at each of the 11 study sites in which GLM had detected consistent (statistically significant) effects of trap location on number of slugs caught. The results indicate that a significant correlation between the pairs of matrices occurred in only 35.7% of the comparisons (Table 6 (A); Tables S1 (A-K) of Forbes *et al.*, 2021)). Taking account of the level of surface activity of slugs in the crops studied, however, in 68.4% of the permutations in which a significant correlation between the pairs of matrices was not found, one or both of those matrices had a mean trap catch of ≤1.5 slugs/trap. This figure rose to 92.9% where mean trap catch was lower than the current UK treatment threshold of 4/trap (Table 6 B). Thus, when lower numbers of slugs are active on the soil surface, differences between the catches of surface refuge traps may be insufficient to detect the effect of trap location on number of slugs caught. When higher numbers of slugs were surface active, however, consistent effects of trap location on catches were readily detected. Hence, patches displayed spatio-temporal stability throughout the growing season of the crop, although they could not always be detected using surface refuge traps, for example when adverse weather conditions resulted in a large proportion of the slug population being below the soil surface.

Table 6. Temporal stability of higher density slug patches at the 11 study sites in which a GLM mixed effects model detected consistent effects of trap location on number of slugs caught between data matrices generated by assessments taken on different dates. Figures show (A) the percentage of permutations of pairs of data matrices at each study site in which a significant correlation between the pairs of matrices was recorded and (B) the percentage of permutations in which a significant correlation between the pairs of matrices was not recorded but one or both assessments were taken when slug surface activity resulted in mean catches of <4 slugs per trap.

Table 6 A

Year	Lancs 1	Shrops 1	Shrops 2	Shrops 3	Shrops 4	Shrops 5	Shrops 7	Lincs 4
2015-16	-	19.0	61.8	28.6	65.4	14.3	-	-
2016-17	22.2	-	10.7	-	-	33.3	-	-
2017-18	-	-	14.3	-	-	-	13.3	0.0

Table 6 B

Year	Lancs 1	Shrops 1	Shrops 2	Shrops 3	Shrops 4	Shrops 5	Shrops 7	Lincs 4
2015-16	-	100.0	100.0	100.0	40.7	100.0	-	-
2016-17	100.0	-	100.0	-	-	100.0	-	-
2017-18	-	-	100.0	-	-	-	100.0	100.0

4.5. Practical assessment of soil characteristics

4.5.1. Current technology/approaches for assessment of the selected soil characteristics in commercial practice

Consultation with industry advisors indicated that current commercial soil mapping approaches and software could, with minor modification, be used to produce maps identifying the predicted locations of patches of higher slug numbers suitable for practical use in arable fields. Assessments relating to all the edaphic factors used in the procedure for predicting the location of patches of higher slug densities are routinely used on an increasing number of farms.

The commercial maps used by the two companies are based on a minimum of 800 sampling points per hectare. Work conducted under the previous project (AHDB no. 2140009118) found that slug patches could be accurately identified using a resolution of 100 sampling points per hectare (Petrovskaya *et al.*, 2018), indicating that commercial assessments would be sufficiently detailed to support the approach. The frequency at which soil assessments are made depend on client requirements, but work under this project investigating the spatio-temporal stability of the soil characteristics of interest indicated that they were sufficiently stable to result in this rarely resulting in the need to conduct dedicated assessments for slug patch treatments.

Electroconductivity scans are routinely carried out, in order to identify variations across fields which may result in yield differences. Principally, the variation detected is a result of differences in soil texture. As EC varies according to soil moisture content soil samples from the different areas can be taken and analysed to determine the exact proportions of sand, silt and clay if required. The prediction of locations in which patches of higher slug numbers will develop relies on relative moisture retention characteristics of the soil, thus within assessment dates, the spatial variation in readings will reflect the soil texture and thus the potential locations of slug patches.

For commercial use, an example of how an EC scan is visualised on the Precision Decisions Mifarm platform is shown in Figure 11. Mifarm allows the different layers of soil mapping to be viewed within the same platform and compared with yield maps (for fields where the data has been collected). Currently these mapping layers are widely used to inform variable seed rates or variable fertiliser applications, but the technology is transferable to the application of slug pellets, pellet application plans could be produced using the current technology.

Figure 11. An example of an EC scan uploaded to the Mifarm (Precision Decisions) platform, an online mapping portal, with multi-layer functionality. The 1 ha sampling area in which slug counts and soil samples were taken is highlighted by the black box.

Assessment and mapping of soil organic matter is also used on an increasing number of farms, and of pH on all relevant arable crops. The Mifarm platform facilitates the incorporation of these maps into the layering procedure for decision making.

4.5.2. Testing electroconductivity scans and soil sampling for prediction of slug patch location in field crops

EC scans were conducted across field sites located at Tibberton, Adeney, and Bridgnorth (Shropshire) and Billinghay (Lincolnshire), including a standard 1-hectare sampling grid.

Slug distribution maps were produced for each 1-hectare sampling grid from data collected using the methods described in sections 3.2.1 (Figure 12 A-D) and were then compared to maps produced from the EC scans, using the standard approach. As EC is dependent on soil moisture content the absolute numbers on the scale for each field vary, but relative levels between different areas (e.g. higher or lower readings) vary in parallel. To link the EC scans more closely to work investigating the effect of soil structure to slug patch location, the resultant maps were used to take soil samples from selected positions across the grid where higher or lower slug numbers were predicted.

The results of the soil analysis from samples taken in different areas of the field (reflecting commercial practice) showed that the silt content within Tibberton varied between 18 and 23 %, Adeney 16 and 29 % and Billinghay 24 – 38 %. Comparison of EC scans (Figure 12 (A-D), soil maps and slug distribution indicate strong overlap between the distribution patterns of EC and soil assessments, and between both EC and soil assessments and slug distribution. For example, in the Tibberton field, the higher slug numbers appear in the area of the field with an intermediate EC (a sandy clay loam), and in the Adeney middle field the area of the field with lower EC (soil type between sandy clay loam and sandy clay).

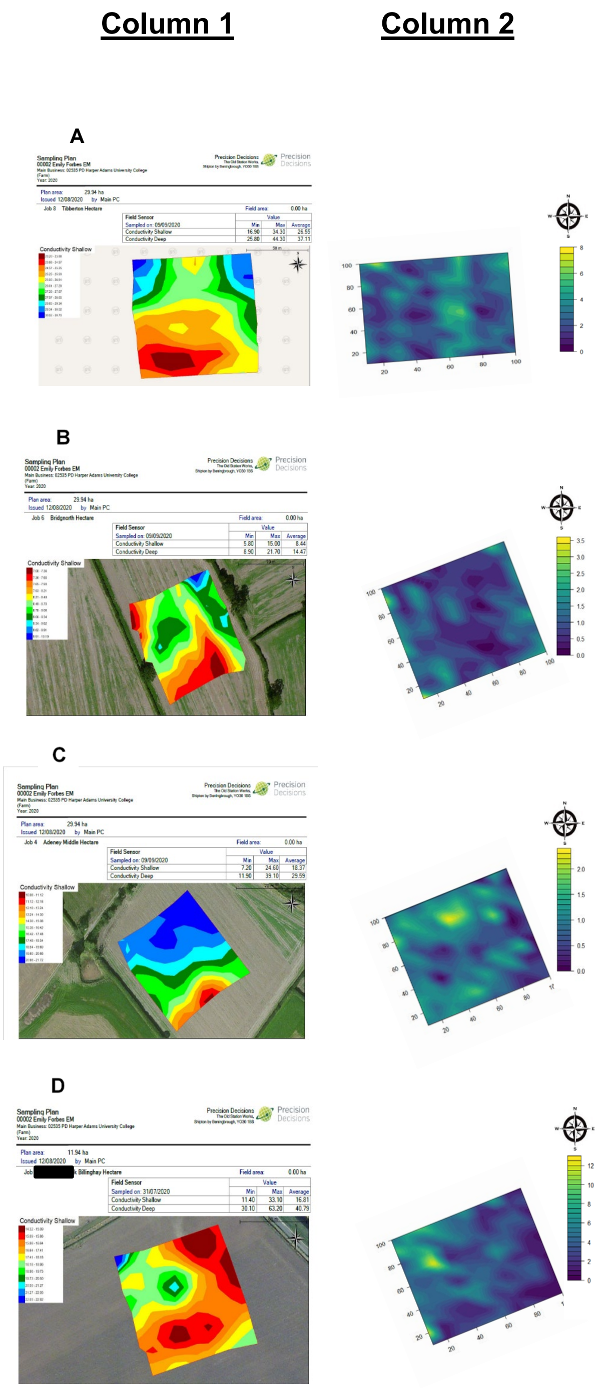
The technique for assessing soil pH and organic matter content used during this project are comparable to techniques used commercially, however, the resolution of sampling is coarser in commercial practice than that used during this research project, which will need to be accounted for when applying the technique in practice. Strong overlap between soil organic matter content and slug distribution was recorded in all fields. A significant overlap between soil pH maps and slug distribution was not recorded in this study, however, reflecting the observation that the pH range in which slugs occur spans most of the range recorded in UK arable fields. Thus, it is likely that the main function of pH analysis in the patch treatment procedure may be to identify fields at the extreme ends of the range which are not tolerated by slugs, obviating the need to apply treatments.

4.6. Integration into a practical system

4.6.1. Integration of project outcomes into a commercially viable targeted treatment approach

A theoretical basis for a prototype targeted pesticide application protocol that allows the selective control of a pest population in agricultural fields was developed. Details of the mathematical progression is provided in a published paper (Petrovskaya *et al*. (2020) and only a summary of the outcomes will be provided here, The approach was based on the assumption of a heterogeneous spatial distribution of the slug population and identifies the areas of high slug density (slug patches), to which pesticide is applied selectively thus differing from many existing commercial protocols in which the entire field is uniformly treated. The model developed demonstrates that the approach results in considerable savings (<40%) in the total crop area treated, and thus the amount of pesticide used, which may also result in a modest positive effect on profit margins.

The most challenging issue that was considered was definition of a spatial patch. It was argued that a generic definition of a patch as any spatial sub-domain with a closed boundary that has a non-zero population density is not efficient when targeted use of pesticide is considered. Under more realistic conditions, the definition of patch will require some additional constraints. Depending on economic and environmental goals, practitioners will require the identification of sufficiently large patches (which allow targeted treatment application) with population density that exceeds a defined level. It was shown that different approaches to defining a patch will lead to different conclusions about the spatial pattern of pest distribution and consequential variability in the area of a crop identified for treatment with pesticides.



A

Sampling Plan
00002 Emily Forbes EM
Main Business: 02535 PD Harper Adams University College (Farm)
Year: 2020

Precision Decisions
The Old Station Works,
Shipton by Beningbrough, YO30 1BS

Plan area: 29.94 ha
Issued 12/08/2020 by Main PC

Job 8 Tibberton Hectare — Field area: 0.00 ha

Field Sensor Sampled on: 09/09/2020	Min	Max	Average
Conductivity Shallow	16.90	34.30	26.55
Conductivity Deep	25.80	44.30	37.11

B

Sampling Plan
00002 Emily Forbes EM
Main Business: 02535 PD Harper Adams University College (Farm)
Year: 2020

Precision Decisions
The Old Station Works,
Shipton by Beningbrough, YO30 1BS

Plan area: 29.94 ha
Issued 12/08/2020 by Main PC

Job 6 Bridgnorth Hectare — Field area: 0.00 ha

Field Sensor Sampled on: 09/09/2020	Min	Max	Average
Conductivity Shallow	5.80	15.00	8.44
Conductivity Deep	8.90	21.70	14.47

C

Sampling Plan
00002 Emily Forbes EM
Main Business: 02535 PD Harper Adams University College (Farm)
Year: 2020

Precision Decisions
The Old Station Works,
Shipton by Beningbrough, YO30 1BS

Plan area: 29.94 ha
Issued 12/08/2020 by Main PC

Job 4 Adeney Middle Hectare — Field area: 0.00 ha

Field Sensor Sampled on: 09/09/2020	Min	Max	Average
Conductivity Shallow	7.20	24.60	18.37
Conductivity Deep	11.90	39.10	29.59

D

Sampling Plan
00002 Emily Forbes EM
Main Business: 02535 PD Harper Adams University College (Farm)
Year: 2020

Precision Decisions
The Old Station Works,
Shipton by Beningbrough, YO30 1BS

Plan area: 11.94 ha
Issued 12/08/2020 by Main PC

Job [redacted]k Billinghay Hectare — Field area: 0.00 ha

Field Sensor Sampled on: 31/07/2020	Min	Max	Average
Conductivity Shallow	11.40	33.10	16.81
Conductivity Deep	30.10	63.20	40.79

Figure 12. Electroconductivity scans of the one hectare sampling grids conducted by Precision Decisions Ltd. (Column 1) in four fields, (A) Tibberton, Shropshire; (B) Bridgnorth, Shropshire; (C) Adeney, Shropshire; (D) Billinghay, Lincolnshire. For each field scans correspond to slug distribution maps in Column 2 and are shown in the same orientation. The X and Y axes show distance between points in metres. Slug distributions are based on the catches of 100 refuge traps

positioned at 10 metre intervals in a 10 by 10 grid, with the first trap at 10, 10. Colour scale represents EC values or slug densities, respectively.

Therefore, in the procedure developed for patch treatment of slugs in the current study, issues relating to patch size, and boundaries being dependent on the chosen “baseline” population density (and the associated need for slug assessments in large areas of the field), are circumvented by the adoption of an alternative approach whereby a combination of environmental (edaphic) factors are used to identify spatial areas in which slug population growth is encouraged, thus generating a stable prediction of where higher density slug patches will form throughout (and between) growing seasons. The approach also identifies patches of a size that facilitates targeted treatments.

The modelling also confirmed that success of the targeted use of pesticide procedure investigated relied upon “temporal stability” of patches. The procedure cannot be applied to species that form volatile patches where the patch boundaries change rapidly with time. Work under the current study has confirmed that slug patches identified in multiple commercial crops in major wheat and oilseed rape growing regions of the UK, displayed substantial spatio-temporal stability that underpins patch treatment. Similarly, the variation in the key edaphic factors used in the procedure to predict the location of those patches also show significant spatio-temporal stability, in some cases for up to at least 8 years, providing an underpinning mechanism for the observation.

The model indicates that careful consideration should be given to the reliability of targeted use of pesticide procedure, demonstrating that in the case of slugs, it can result in live/active pests remaining in locations surrounding those that have been targeted. These may form a nucleus for pest resurgence after the efficacy of the pesticide has declined, resulting in reformation of patches, particularly if, as in this case, there is an environmental driver for clustering in those areas. Aspects of the biology (principally a limited foraging range) result in this not being as significant a problem for slug control as in other pests, and does not negate the overall efficacy of the approach. If required in the future, however, the model offers a basis for the recalculation of thresholds to contribute to further improvements to sustainability by application of reduced volumes of pesticide through even more careful targeting.

Finally, a challenging question closely related to the use of thresholds, is the issue of accurate evaluation of the pest abundance. While average trap counts have long been used to provide information on population abundance in ecological applications or when making pest management decisions (Anderson *et al*., 2013; Disney, 1986; Walters *et al*., 2003), it has been recently demonstrated (Petrovskaya, 2018; Petrovskaya and Embleton, 2013) that the spatial heterogeneity (patches) presenting in a spatial pattern of the population can make the problem of population abundance evaluation challenging. The problem is exacerbated when a coarse sampling grid is employed in a monitoring/control protocol (Petrovskaya *et al.,* 2018). Historical success of the recommended approaches for assessment linked to the AHDB action thresholds for slugs suggest that sufficient accuracy has been achieved and accordingly, it was concluded that the patch treatment procedure developed should initially involve utilizing this threshold to make treatment decisions, then patch-treating those fields where it is warranted rather than applying blanket treatments to the whole crop.

4.6.2. Prototype procedure for patch treatment of slug populations with control agents in commercial arable fields

The procedure developed relies on four main components.

1. The established thresholds for OSR and wheat (AHDB 2018) recommend that slug populations are assessed by setting nine baited refuge traps (13 in fields larger than 20 ha) in a ‘W’ pattern, spread over the entire field. Traps are left overnight and the number of slugs (noting slime trails) are counted early the following morning, while the soil surface is still moist. The counts are interpreted using a series of action thresholds depending on crop type and other factors. For example, in winter cereals between sowing and first tillering (growth stage 21) broadcasting a slug pellet treatment is advised if a mean or trap count of four or more slugs is recorded.

   The patch treatment procedure commences by using the same action thresholds to determine the need to apply control measures, but if treatment is triggered slug pellets are targeted only at areas of higher slug numbers, rather than broadcasting over the whole field.

2. If application of molluscicide treatments are required, the location of patches of higher slug numbers are defined using assessments of soil structure (electroconductivity scanning) , soil organic matter (if soil improvement techniques that affect organic matter content have not been used since the last assessment, see section 4.4.1) and pH. Soil pH becomes significant only at the extreme ends of the range normally found in arable crops, thus is likely to affect slug distributions in only a few crops.

   To ensure the approach remains cost effective, data from assessments taken for other crop husbandry purposes can be re-used and research into spatio-temporal stability of these characteristics suggest that the datasets remain usable for at least 5-8 years. Soil structure is thought to be the main driver of slug distribution in most fields, and in the event of satisfactory assessment data on this factor not being available, the option of broadcasting slug pellets across the whole field remains available.

3. When mapping soil structure, organic matter and pH, current commercial practice is to use GPS to locate the precise location in the field in which each reading (electroconductivity scanning) or sample (organic matter, pH) is taken. Standard (automated) software similar to that currently offered by the soil mapping company, Precision Decisions Ltd., is available and widely used commercially to produce detailed maps of each soil factor. These maps are layered (again using existing software) to predict the locations in which patches of higher slug numbers will be found. The whole process can therefore be automated with, at most, small modifications to existing software.

4. The layered maps provide a basis from which to target pesticide applications, and the necessary technology to achieve this is widely used for other purposes. For example, spatially referenced (by GPS) soil fertility maps with appropriate resolution, are used to target fertilizer applications using GPS enabled spreaders. A similar approach can be employed for patch treatment using slug pellets.

The prototype procedure therefore applies the outcomes of the research using existing technology that is familiar to farmers/agronomists through other on-farm activities. The essential features are the re-use of soil assessments taken for other husbandry purposes, the automation of soil map integration (layering) and spatial referencing, and the potential to use existing equipment, the latter obviating the need to purchase new machinery.

4.6.3. Principle costs and cost-sharing

Integrating datasets from 167 assessments of 1-hectare plots established in 22 fields in major crop growing regions of the England and Wales and over a period of three years, the model developed in section 4.6.1 suggests that significant reductions in the area treated with molluscicides can be achieved by the patch treatment procedure. Potentially (with the caveat noted in section 4.6.1) up to 40% of the area treated using a whole field broadcast application could be left untreated with little impact on the suppression of slug treatment during the crop damage window. In a subsequent field trial, a higher figure of ≤70% of the plot area was left untreated, but as this related to 1-hectare plots in a single field for the following calculations the lower figure has been used.

During the cropping season reported on by Garthwaite *et al*. (2019) an estimated total of 386,920 hectares of winter sown oilseed rape received an average of 2 slug pellet applications, with a combined total of 773,840 hectares treated with molluscicides. If 40% of this area was left untreated following targeted patch treatment, then applications of molluscicides to a total of 309,536 hectares would have been saved. This represents a significant reduction in environmental impact. Calculating a monetary value for the reduced environmental consequences is a specialist field and will not be attempted here.

If growers are to consider adopting targeted patch treatments, then slug control costs should at minimum be unchanged in comparison to the current approaches, and preferably offer an increased profit margin. The focus on integration of this research programme with current commercial practices result in the equipment and software required being similar to those already used for other on-farm purposes. The necessary soil assessments are already undertaken on an increasing number of farms (e.g. fertilizer applications and for other decision making), and the spatio-temporal stability of the essential soil characteristics permit the re-use of this existing data for slug assessments. Software required for the production and layering of soil maps is also currently available and used commercially, again obviating the need for significant investment. Relating these maps to precise positions in the field to target applications relies on GPS, which is commonly fitted to relevant farm machinery and is, for example, used for variable (targeted) fertilizer applications. Finally, the speed at which current application equipment can be turned on and off also facilitates targeting of patches of higher slug densities. Thus, use of existing machinery and software should minimize investment costs, and importantly the re-use of soil maps already produced for other purposes will allow cost sharing. Collating these factors indicates that the patch treatment approach will, with the exception of the cost savings associated with purchase of molluscicides, not affect the current costs of growing a crop.

Growers will consider the cost-benefit of using the approach at the farm or individual crop level. With regard to savings emerging from lower use of molluscicides, Evans (2020) provided a guide to the cost of applying the maximum single dose of ferric phosphate products, estimating it to be between £29-45/ha. Several products are approved for professional use on field crops in the UK, including Sluxx, Sluxx HP, IronMax Pro, Aristo IP, Derrex, Fe-est, Fe-lyn, Ferrimax Pro, IronFlexx, IronMax Pro, Iroxx, Slugger, Sluggo and X-ECUTE. Independent industry consultation confirmed that the recommended maximum application rate of one of these products, Derrex, which is registered for slug control in edible and non-edible crops, is 7kg/hectare translating to an in-field cost at the lower end of the above range (Certis, 2021).

Assuming that only 40% of the area currently treated would require pesticide application under the new approach, at the lower end of the range the cost of pesticide would be reduced to £11.6/hectare, rising to £18/hectare at the upper end of the range. Assuming that each hectare of land on which control measures against slugs are applied receives an average of 2 treatments with a cost of treating of £29/hectare, a total saving of £23.2 might be achieved, rising to £36 if application costs are at the £45 end of the range. Comparison with a recent Gross Margin Budget (Table 7) indicates that as equipment and historical/current assessments of edaphic factors can be re-used for slug patch location, use of a patch treatment approach is either cost neutral or has a small positive effect on profit margins. For example, if only a single application of molluscicides was made to the crop, the estimated gross margin increased from £222/t to £233/t (approximately 5%) with a proportionally higher increase if two applications are required.

Table 7. Gross Margin budget for winter sown oilseed rape (Data from John Nix Pocketbook for Farm Management (2019)

Production level	**Low**	**Average**	**High**	
Yield t/ha (t/ac)	3.00 (1,2)	3.5 (1,4)	4.00 (1,6)	
	£	£	£	£/t
Output at £350/tonne	1050 (425)	1225 (496)	1400 (567)	350
Variable costs t/ha (t/ac):				
Seed		60 (24)		17
Fertilizer		155 (63)		44
Pesticides		234 (95)		67
Total variable costs		449 (182)		128
Gross Margin	601 (244)	776 (314)	951 (385)	222

Fertilizer basis 3.5.t/ha

Nutrient	Kg t	Kg Ha	£/Ha
N	54	190	110
P	14	49	28
K	11	39	16
	Seed write-off (8%)		

Seed

£/Ha C	54
£/Ha Hy	70
£/Ha HSS	40
C HyHSS	35:30:35
Kg/Ha	5.5

Treatments

Pesticides	£201
PGRs	£18
Other	£15

Prices: The price used for the 2021 crop is £330/tonne plus oil bonuses at 44% oil content. The bonus is paid on the percentage of oil over 40% at 1.5 times the sale value of the crop and an equal but opposite penalty below 40%. For example, in this case, the bonus is on 4% oil x £330 x 1.5 - £19.80 (Figures are rounded to the nearest £5 in the margin).

5. Discussion

Pesticide application is the most widely used means of pest control and it has been estimated that around 3×10^9 kg of pesticides are used across the globe per year (Pimentel, 2009). However, the indiscriminate use of pesticides can have serious negative consequences. Application of pesticides is costly and can risk damage to the environment (Jepson and Thacker, 1990). Pesticides are known to contribute to air, soil and water pollution (DEFRA, 2016) and there is also some evidence linking their use to human illnesses (Alavanja *et al*., 2013; Pimentel and Greiner, 1997). The overuse of pesticides can lead to insect resistance making future management a more difficult task (Alyokhin *et al*., 2008). Finally, lethal or sub- lethal effects on non-target organisms such as natural enemies (Sohrabi *et al*., 2013) can result in resurgence in the pest population or emergence of secondary pests. Such risks are addressed by legislation governing the development and subsequent use of pesticidal products, and by technology that improves targeting and reduces drift, but there is a widespread recognition of the requirement to reduce and optimise the volumes applied (Matthews, 2014; 2016).

Increased pressure to reduce the use of pesticides in agricultural crops results in an urgent need for new approaches to pest control that both reduce the number of applications in commercial agricultural fields and make those applications more precise. The concept of spatially targeted pesticide application to control pest population has already received the attention of researchers (e.g. see Archard *et al*., 2004; Brown *et al.,* 2008; Pimentel, 1997; Sotherton *et al*., 1993. Among other examples, the study in Brenner *et al*. (1998) has been focused on the probability of the presence of the pest in a spatial environment, allowing for the targeted use of pesticide in spatial areas where there is a high probability of pest presence. Probability mapping has also been done on larger scales in agriculture (Fleischer *et al*., 1999) where sampling has been used to generate a probability threshold map, a contour map showing the probability of the number of pests within a known area exceeding a defined threshold. There have also been discussions on weed detection and targeted spraying of herbicide (Miller, 2003) as well as efforts to produce a system of automated robotic pesticide spraying over target areas for use in greenhouses (Sammons *et al*., 2005). Most recently the concept of targeting molluscicide treatments at the spatially and temporally stable patches of higher slug densities that have been shown to occur in arable crops have been investigated in the field (Forbes *et al*., 2017). Such studies, however, have not related targeted use of pesticides with the need to develop a monitoring and control protocol that takes account of the locations of spatial patches where the population density is high.

In this study a prototype protocol is developed for targeted use of pesticides where the above issue is addressed for the grey field slug. The species is an important pest of a wide range of agricultural and horticultural crops, which results in significant economic losses in most years (Nichols, 2014; Twining *et al*., 2009). For many years slug control in arable crops has relied on molluscicide pellets applied to the entire field when the slug population exceeds defined thresholds. It has been reported in numerous studies (Archard *et al*., 2004; Bohan *et a*l., 2000; Forbes *et al.,* 2017) that the spatio-temporal dynamics of the its populations results in heterogeneous spatial patterns of slug density in arable fields whereby readily detected patches of higher slug numbers are interspersed within areas of lower slug densities irrespective of the population size. A patchy distribution of slugs offers significant potential for reducing use of pesticides in agricultural fields. If a commercially viable method of identifying their location and size can be established then application of pesticides may be targeted at high slug density patches alone, leaving areas with lower slug numbers untreated.

5.1 Industry consultation

Feedback and involvement from five broad industry sectors has been sought on a continual basis throughout the project through the Harper Adams University Centre for Integrated Pest Management. The discussions have centred on commercial soil assessment and associated mapping software, application technology, GPS and pellet manufacturers, agronomy and farmers, and trade press, industry events and other media.

A primary driver of the definition and design of the work areas addressed under this project has been consultation and collaboration with key industry sectors, which has provided an understanding of the state-of-the art technology that can be used within the patch treatment procedure, insight into commercial constraints, concerns and priorities, and in one case both anonymized historical datasets arising from commercial soil assessments made for clients, and soil scans at experimental sites (see section 4.1.2 - 4.1.5)). Travel restrictions imposed as a result of the Covid-19 pandemic that would have severely restricted the extent of the work that could be delivered in some aspects of the project, were largely overcome as a result of the datasets provided. In addition to commercial technology and service providers, an extensive range of agronomists and farmers were consulted, who raised a range of issues and questions that should be considered during both the conduct of the research and integration of the findings into a provisional procedure (see section 4.1.1). These focused on three main areas, feasibility of developing a commercially acceptable procedure within the constraints imposed by slug biology, reliability of the developing procedure, and practicality of the system (with particular emphasis on the potential for it to be integrated with wider farm activities and cost-benefit issues). The influence of these issues and questions on project outcomes are summarized below.

In all cases, consultation was structured to encourage, where appropriate, direct communication between representatives of different sectors (e.g. to confirm the potential to link soil mapping with GPS to enable automated targeting and delivery of slug pellets to patches of higher slug densities. In addition, the information required was obtained sufficiently early to ensure that experimental work was designed to take account of the commercial potential and constraints, facilitating interpretation of the outcomes from a commercial perspective and supporting the design of a practical procedure for patch treatment (see section 4.6.2).

5.2 Development of a patch treatment procedure: Treatment Action threshold

The integration of the project output and those of published studies into a provisional patch treatment procedure commenced with consideration of the approach to the initial decision to apply molluscicides. Patches of higher slug densities form in areas of the field in which edaphic factors are favourable to their survival and reproduction (Carrick, 1942; Gould, 1961; South, 1992; Schley & Bees, 2002; Odina *et al*., 2004; Willis *et al*., 2008), and behavioural responses to conspecifics have been shown to result in movement patterns in the field which reinforce patch stability (Ellis *et al*., 2020). Although patch treatment targets areas with higher slug density and therefore impact is focused where the greatest reduction in crop damage will be achieved, leaving some areas (with lower slug densities) untreated is likely to result in a lower overall suppression of the slug population across the field. Currently, it is recommended that molluscicides be applied when an average of 4 slugs per trap are recorded in surface refuge traps set in a standing crop (AHDB, 2018). The expected slightly lower population suppression resulting from patch treatment may, however, indicate a need to lower the action threshold to ensure the post-treatment infestation is similar to that obtained following full field applications. If, however, crop damage is not economically significant in areas which remain untreated, then provided the surviving slugs do not move to the more favourable (treated) areas, this may not be necessary. A recent report has indicated that crops may be more tolerant of slug damage than the current thresholds allow for, strengthening the assumption that interpatch areas may not be subject to significant crop loss (ADAS, 2010).To establish the optimum approach for treatment decisions, a theoretical basis for the prototype targeted pesticide application procedure was developed and used to compare four different putative action thresholds (Petrovskaya *et al*., 2020). Based on this work, we concluded that the AHDB threshold continued to identify the need to control slugs under the patch treatment approach, a finding that is supported by field work conducted by the project group which demonstrated that foraging slugs remain in a restricted area for extended time periods (Forbes *et al*., 2020), thus are less likely to rapidly re-infest areas with more favourable edaphic conditions. This component of the project addressed grower concern that patch treatment would require a new treatment threshold that was more labour intensive than the current approach, and offers advantages of grower familiarity.

5.3 Development of a patch treatment procedure: Soil analysis- slug patch location

Carrick (1942) first suggested that edaphic factors, such as pH, soil moisture and organic matter, may influence the location of areas of higher slug numbers in arable fields. Few field studies investigating the relationship between slugs and soil characteristics have been conducted subsequently, with the majority of research being carried out under laboratory conditions and focusing on individual soil characteristics (moisture and temperature, Getz, 1959; pH, Wareborn, 1975; temperature, Wareing & Bailey, 1985; organic matter, Speiser, 1999; temperature, Cook, 2004). The emerging trend from the literature suggests that pH, soil moisture and factors affecting seed bed condition are the key to understanding the distribution of slugs in arable fields.

South (1965) considered the discontinuous distribution of *D. reticulatum* in relation to several environmental factors in a grassland field, including distance from the headland, organic matter content of the soil, moisture and the stone coverage (as a percentage of the soil surface), but none of these factors were demonstrated to be significantly correlated with the distribution of slugs. More recently, the distribution of 17 species of terrestrial gastropods was related to a combination of soil characteristics in 10 km by 10 km grid squares in Iberia, using three samples from 124 grid squares taken in each year of the three-year study (Ondina *et.al.*, 2004). Three groupings of slugs were identified, the first showing a preference for acidic soil with a high proportion of coarse sand (>56.4 %), the second (including *D. reticulatum*) were associated with wetter, less acidic soil with high proportions of silt and clay and a third group which showed no preference. More specifically, *D. reticulatum* were found to occur in higher numbers in soils with high pH (5.6-8.5) and calcium levels (5.3-26.0 %), an intermediate level of moisture (36.8-41.6 %) and gravel fraction (8.3-14.0 %) and a low coarse sand fraction (14.7-24.2 %), low level aeration (22.3-27.1 %) and aluminium content (0.1-0.6 %) (Ondina *et.al*, 2004).

More recent work investigating the causes of the heterogenous distribution of slugs in arable fields has focused on laboratory and preliminary field studies of soil characteristics (Forbes, 2019). Strong similarities between the outcomes of laboratory and field experiments were noted that together identified candidate characteristics that may explain the location of patches of higher slug densities. Laboratory soil gradients were used to investigate slug responses to pH, soil moisture and temperature. Clear preferences for moist (but not waterlogged) soils, and soil temperatures between 5°C and 14°C (when compared to the more extreme temperatures offered; 4°C and 24°C). In individual field experiments areas with higher slug densities were correlated with soil organic matter content, pH, soil texture, bulk density and porosity, but no such relationship was found for an individual factor in more than two fields. Overall, in the laboratory, slugs displayed a strong response to soil moisture but in the field moisture levels in the upper soil horizons are subject to variation due to weather and therefore may provide an unreliable predictor of patch location. However, variable moisture retention characteristics of soil will affect the rate of drying resulting in some locations displaying generally higher moisture levels, thus offering a more favourable habitat. Moisture retention is affected by several soil factors including soil texture, bulk density, and porosity, each of which were correlated to patch location in the field experiments suggesting an underpinning mechanism.

Higher organic matter content also affects the water holding capacity of soil in addition to providing a food source, and influencing pH (Carrick, 1942; Franzluebbers, 2002; Hudson, 1994). In soils with high clay content increasing organic matter content can also improve water infiltration through the soil (Boekel, 1963; Hillel, 2008), reducing the incidence of waterlogging (Carrick, 1942). It also improves structure and stability in soils and increases coherence of soil particles leading to soil aggregation, which increases the size of pores between aggregates therefore decreasing the bulk density of the soil (Bauer, 1974; Keller and Håkansson, 2010). As organic matter content varies widely within and between agricultural fields, depending on factors such as cultivation methods and crop rotations (Franzluebbers, 2002), however, its effect on several soil properties that can impact slug numbers may vary. It is therefore an important factor in determining slug abundance but in isolation may be a less reliable predictor of slug patch location.

A significant relationship between slug numbers and pH was found in two of the six fields studied by (Forbes, 2019). The literature reports variable results regarding the effect of pH on slug abundance. Boycott (1934) collated the results of a range of studies to investigate the relationship between soil pH and abundance of several slug species (not including *D. reticulatum*) and found no relationship between soil pH and slug distribution. Investigation of the relationship between pH and slug abundance in 41 potato fields in Scotland found no correlation between soil pH, the density of slugs or the level of damage to the crop, with the highest slug densities (including *D. reticulatum*) occurring in soils with pH 5.4-6.9 with the lowest slug numbers in pH 4.8-7.0 (Carrick, 1942). Conversely, a study by Ondina *et al.* (2004) demonstrated that *D. reticulatum* preferred soils with high pH (>5.6). The range of pH levels studied by Ondina *et al.* (2004) was wider (3.6-8.1) than that in the earlier study of potato fields (4.8–7.2). Thus, pH may have a role in determining slug abundance in soils with a lower pH but within the range typically found in arable fields in the UK (5.5-7.5; Skinner and Todd, 1998) it may not be a factor restricting the location of slug patches in most cases. It was, however, retained as a factor in the current work as it may be important at the extreme ends of the normal range encountered in UK fields.

The current study investigated five soil factors as potential predictors of the locations in which patches of higher slug numbers would develop, including pH, organic matter, soil texture, bulk density and particle density. Previous work suggested that it was unlikely that any individual factor would be sufficient to accurately explain location, and a model utilizing combinations of factors may have to be developed to increase the strength of predictions. The outcomes build on the findings of Forbes (2019), with significant relationships between populations of surface-active slugs and soil texture (% silt, % sand or % clay), and organic matter content, factors which all affect moisture retention amongst other advantages for slugs. Comparison of the soil maps generated from the data collected confirmed that slug distribution is the result of a complex interaction between all three factors, resulting in no individual characteristic fully accounting for the variation in slug numbers across the field. Thus, the most accurate prediction of patch location is likely to be achieved by these three factors in combination. Although slug activity was not found to be related to bulk density, particle density or pH, the latter was retained for the combined model as it identifies those fields at the extremes of the normal range found in UK fields in which there is lower risk of slug damage. Inclusion of pH may reduce unnecessary use of molluscicides under such conditions (Skinner and Todd, 1998). Consultation with representatives of the industry sectors offering soil assessment/mapping services, and GPS/pellet manufacturers confirmed that assessments of organic matter and pH, and electroconductivity assessments which relate to and serve as a proxy for soil structure, are all routinely assessed in arable fields and software was available that would allow current commercial scans to be utilized in slug patch prediction models.

The model combining the four soil characteristics successfully predicted the location of high slug densities (defined using an experimental definition as areas in which a mean of 4 slugs/trap were recorded) in 81% of cases the 2019/20 cropping season with a lower success (40%) in 2020/21. There were low slug populations present in the study field in 2020/21 which is known to make accurate identification of the patches using surface refuge traps difficult, potentially contributing to the lower success rate (Forbes *et al*., 2021). However, further refinement and testing of the model is required before release for use in commercial practice, and it is anticipated that this will further improve the accuracy of forecasting of the location of areas with high slug densities.

Agronomists and farmers were aware that use of surface refuge traps to locate slug patches would be unlikely to be cost-effective at the field scale and required a commercially realistic approach to be developed. They were also aware that use of soil characteristics was being considered and asked whether the factors which could be used were known. The project has addressed both these questions. Assessing the variation in edaphic factors across whole fields offers a potential solution to this issue, however, before it can be made available for commercial use, as indicated above, refinement and further testing/verification of the current model coupled with confirmation that the spatio-temporal stability of the relevant soil characteristics is sufficient to support the procedure was needed. Similarly, confirmation that appropriate commercial software/hardware is available to deliver the system was required. Industry consultation had addressed issues surrounding soil assessment when selecting the edaphic factors to include in the model, and discussions with GPS and pellet manufacturers indicated that current technology and associated software needed to utilize the resultant soil maps could be readily adapted for targeting of slug pellet applications. Issues relating to the spatio-temporal stability of soil characteristics are addressed below.

5.4 Development of a patch treatment procedure: Spatio temporal stability of soil characteristics

If in-field variability of the selected soil characteristics are to be used to predict the location of patches of higher slug densities, commercial viability relies on the re-use of assessments currently made for other crop husbandry decisions. As timing of these assessments will rely on other on-farm activities, sufficient spatio-temporal stability of the soil factors is essential.

Historical soil assessments for pH and organic matter content taken from a standard grid established in an identical position in experimental fields located in Shropshire and Leicestershire in two consecutive cropping seasons were compared. A very high degree of spatial stability of pH assessments in two consecutive crops was detected in both fields. Organic matter content of the soil was also found to be stable in the Shropshire field, whereas a non-significant trend towards spatial similarity was detected in the Leicestershire field. The reduced stability resulted from the use of cover crops which are ploughed back into the soil, significantly affecting variability of soil organic matter in the subsequent crop (AHDB, 2015). Thus, where cover crops are routinely used, more frequent assessment of organic matter content may be required.

Stability of in-field spatial variation of soil structure and soil pH was investigated using data from commercial assessments conducted in clients' fields in Yorkshire by the soil mapping company Precision Decisions Ltd. The between season temporal stability of in-field variation in soil pH that was established using data from the grid sampling technique, was also detected from the full field commercial assessments. Data from a sequence of three assessments with an interval of four years between each (2011, 2015, 2019) showed that there were highly significant relationships between the pattern of soil pH recorded between each sequential sample, indicating stability over each four-year period. A similarly highly significant relationship was found when the first and last sample were compared, extending the period of stability to 8 years.

Electroconductivity scanning was recommended as a commercially viable proxy for soil structure assessment that is also conducted for other on-farm decision making offering the potential for cost-sharing of data in the proposed slug patch location approach (see section 5.3). Precision Decisions Ltd. provided historical soil scan data from clients' fields with a period of up to 8 years between assessments. A strong relationship was found between the spatial variation of scanning data across fields, even with the 8-year gap between assessments, again indicating a high degree of spatio-temporal stability in electroconductivity/soil structure.

Thus, spatio-temporal stability of all selected edaphic factors was found to be sufficiently stable to be used in the patch treatment approach, despite annual cultivation of the fields assessed. However, care must be taken when techniques such as cover cropping or manuring are used to increase soil fertility if organic matter content of soil is included in predictive models, as these can significantly affect the levels in different locations of the field.

The work completed addresses one of the main concerns commonly raised by agronomists and farmers. Dedicated soil assessments for patch location will not be required, thus reducing the cost of the patch treatment approach significantly where assessment data is shared with other agronomic uses.

5.5 Development of a patch treatment procedure: Spatio temporal stability of slug patches

If the heterogenous distribution of slugs in arable fields is to offer the potential for reducing molluscicide use while maintaining effective control of slug damage in commercial crops by spatially targeting applications to specific areas containing higher slug numbers, such slug patches should be a characteristic of populations in all crops that are susceptible to damage, and display sufficient spatio-temporal stability. Current evidence demonstrating that slug patches are often found in arable crops and are stable (at least within a growing season) is based on data collected from relatively few crops and usually over short time periods, and requires empirical confirmation. In the current work the existence of identifiable slug patches was investigated using hotspot analysis to locate areas with significantly higher than expected slug numbers than would be predicted if a random distribution was assumed. Higher density patches were identified in all of the 22 commercial crops (six crop types) studied, and in all but five (3.0 %) of the assessment visits undertaken. Failure to locate any patches occurred in just a single visit to each of five different fields, and in each case slug counts were very low at the time of the assessment (<0.07 slugs per trap). No effect of region on the spatial distribution of slugs within fields was evident when western and eastern parts of the UK were compared. Thus, this study critically re-examines previous findings (Forbes *et al*., 2017; Nicholls, 2014; Ramsden *et al*., 2017; South, 1992) that slugs display a heterogeneous distribution in arable fields, to prove that the existence of patches of higher slug numbers separated by areas with lower slug activity is a characteristic property occurring across a range of crop types and geographical regions.

The intermittent failure to locate slug patches in sequential assessments of the same field has also been noted in a previous study (Forbes *et al*., 2017) and requires explanation. Several methods for assessing slug populations have been developed with soil washing, soil flooding, defined area traps and refuge trapping being most commonly used for research (Archard *et al*., 2004; Ferguson & Hanks, 1990; Glen *et al*., 2003; Howlett *et al*., 2005; South, 1992). Although their efficacy for establishing absolute slug populations is limited, there is evidence that surface refuge traps can be used successfully to determine the relative numbers of slugs that are active on the soil surface in different areas of fields, and were thus selected for use in trapping grids in the current work (South, 1992). Slug activity on the soil surface (thus catches) are known to be affected by environmental factors such as soil moisture and temperature, which vary throughout the growing season (Choi *et al*., 2004; Shirley, *et al*., 2001; Taylor, 1961; Young *et al*., 1993). For example, periods with temperatures of <13 or >17 °C (Wareing & Bailey, 1985), or prolonged periods of low rainfall can result in a significant proportion of the population retreating to a protected environment below the soil surface where they cannot be detected using refuge traps until more favourable conditions return (South, 1992). Thus, the failure to detect any patches in six of the assessments may have been the result of adverse physical conditions that resulted in the observed very low trap catches and associated small differences between the number of slugs recorded in individual traps in the grid. Further, successful suppression of slug populations following application of slug pellets to some fields may have contributed to masking of the location of the patches prone to harbouring higher slug numbers by significantly lowering trap catches across the sampling grid (particularly within those patches). The fields used in this study were all situated on commercial farms, and all had received molluscicide treatments. Thus although, this may in a few cases have affected detection of slug patches, the results of the hot spot analysis suggest that treatments did not prevent their formation and cohesion.

A more detailed analysis compared the pattern of spatial clustering described by the data matrices of slug numbers recorded on each assessment date in each of the 11 crops in which consistent differences had been identified. Significant correlations between the cluster (patch) locations were readily located in fields with higher slug numbers. In more than 90% of the cases where significant correlations were not obtained, mean trap catches in one or both data matrices were lower than 4/trap, the current UK treatment threshold in winter wheat and oilseed rape. Thus, where accurate data on slug surface activity was available, patches displayed spatio-temporal stability throughout the period in which crop assessments were made, although they could not be detected using surface refuge traps during periods of adverse weather conditions when a large proportion of the slug population would have been situated below the soil surface. Under such circumstances, however, the results of this study suggest that the difficulty of detection would not occur when slug numbers exceed current action thresholds, so it would be unlikely to adversely affect the concept of targeted treatments.

In the context of commercial agriculture, perimeter-core slug density gradients that can result in a broad zone of generally higher slug numbers near crop edges, may allow easier detection of patches using refuge traps in such areas (South, 1992). If, however, environmental factors influence the locations in which patches form (Forbes *et al*., 2017), such gradients are unlikely to significantly affect their number or position. In practice, most molluscicide applications are made during a period encompassing the establishment and early growth of crops, but information regarding the timing of the formation of slug aggregations is sparse. Thus, further work focused on the spatial stability of slug patches during the period spanning two sequential crops in commercial rotations would be a useful addition to our understanding of slug distribution in this context.

The mobility of slugs is key to understanding the mechanisms underpinning the formation and cohesion of population patches and thus their temporal stability. A recent study in which movement of individual slugs was followed for a period of five weeks using radio frequency identification technology, demonstrated that most (~80%) foraged within a limited area, with the mean distance travelled from the release point being 78.7 ± 33.7 cm in spring and 101.9 ± 24.1 cm in autumn [Forbes *et al*., 2020). This suggests that the limited locomotor behaviour may promote the patchy distribution observed during the crop growing season in the current work. Few studies have addressed the behavioural mechanisms leading to the limited foraging area of the grey field slug but, in other organisms, density dependent individual movement is known to contribute to pronounced spatial heterogeneity and the stability of patches containing higher population density (Ellis & Petrovskaya (a, b), 2020; Grünbaum & Okubo, 1994; Gueron *et al*., 1996; Tyutyunov *et al*., 2004). Preliminary work on the grey field slug has indicated that, within areas of higher slug density (i.e. in the presence of conspecifics), individuals move more slowly and for shorter distances, spend more time immobile, and display a strongly biased distribution of turning angles. It was shown that, consistently with these factors, the area occupied by a patch grows more slowly in the presence of higher slug densities, arguably indicating that density dependence of individual slug movement enhances patch stability (Ellis *et al*., 2020).

The work demonstrating the spatio-temporal stability of slug patches has comprehensively addressed several questions and concerns of the agronomists and farmers consulted during the project. Patches were found to occur in all arable fields, although on very rare occasions assessments failed to identify any patches in a field during an individual assessment visit Forbes *et al*., 2021). This, however, was shown to be the result of slug responses to temporarily adverse environmental conditions (e.g. dry soil surface and high temperatures) that caused them to retreat into the upper soil horizons for protection where they could not be assessed by the surface refuge traps used in the experimental work. In all cases, slug patches were detected at all subsequent assessment visit to the field. The location of the slug patches could be reliably established using the grid trapping design developed for this work programme, giving confidence that the data used in the development of the patch treatment procedure accurately reflects slug distribution in the arable fields (Petrovskaya *et al*., 2018). Although a reliable method, it is recognised that it would be impractical for slug patch location for commercial purposes, leading to the development of the new approach using selected edaphic factors. Importantly, the spatio-temporal stability of the patches resulted in them occurring in the same places throughout the window in which crop protection measures are used (Forbes *et al*., 2021), obviating the need to repeated assessments during the slug damage window. Due to adverse environmental conditions some patches could not be detected using the surface refuge traps at all assessment visits to fields, but where this occurred, they reappeared in the same positions following rainfall or during periods with more favourable temperature conditions. Spatio-temporal stability of patches of higher slug density was a universal feature of the extensive datasets analysed irrespective of the crops grown, or geographical position within the UK, and not simply a feature of a sub-set of the fields studied. A behavioural mechanism underpinning the stability has been established by the programme team (Ellis *et al*., 2020; Forbes *et al*., 2020), giving further confidence in the conclusions.

5.6 *Development of a patch treatment procedure: Use of soil maps*

The use of soil structure, and soil organic matter content or pH to define the location of patches of higher slug densities requires automation of both assessments and data integration. Industry consultation confirmed that the factors selected for use in the patch treatment procedure were currently assessed commercially for other husbandry purposes, and that the available machinery and software can be readily adapted for new uses. The current resolution of soil maps generated for delivery of commercial services is higher than the 100 sampling points per hectare that was used in our study to define both slug patch location and edges (Petrovskaya *et al.*, 2018; David Howard, Hutchinsons Ltd. pers. com), suggesting that it would not be a limiting factor. Thus, both the spatio-temporal stability of the soil characteristics (see section 5.5) and assessment resolution allows the re-use of datasets from electroconductivity scans or organic matter/pH assessments taken for other purposes, significantly affecting (positively) the cost-efficacy of the procedure.

Integration and interpretation of multiple datasets to inform pest management actions can be problematic, with complexity often threatening to prevent uptake of new approaches by the industry (Walters *et al.*, 2003). In this case, however, the software that would be needed to analyse and interpret the data required for our procedure has already been developed with wide uptake by the industry, for example to guide differential fertilizer applications to areas of fields with lower fertility levels. Individual in-field assessment points are spatially located using GPS, supporting the generation of field-wide soil maps documenting variability in electroconductivity (the proxy for soil structure), and soil organic matter and pH, using software similar to that developed and operated by Precision Decisions Ltd., the representative company from the industry sector consulted as part of this study. Similarly, standard procedures/software are available for layering the maps, which can be re-purposed to identify areas prone to the development of patches of higher slug densities. Thus, spatially defined locations for the targeting of slug pellets can be automated and digital maps transferred to a pelleter. GPS on the applicator can then be used in conjunction with the predictive maps to turn application on and off as the pelleter enters and leaves areas requiring treatment. Thus, existing technology which has the advantage of farmer familiarity facilitates the automation of patch treatment (Matthews 2014, 2016), addressing the problem documented by Walters *et al.* (2003).

5.6 *Development of a patch treatment procedure: Testing the procedure*

Field testing/verification of the new procedure was limited by travel restrictions resulting from the Covid-19 pandemic, preventing pre-screening of candidate fields and resulting in associated low slug population at the experimental site. Two treatments ("broadcast" and "patch" treatments) were applied to 1 ha plots, slug distribution maps were created, with slug pellets applied only to areas with higher slug numbers in the "patch" treatment. A cumulative total of only 30% of the area was treated in this experiment, but no significant differences in slug populations between the two approaches were identified either before application of slug pellets (confirming that direct comparison of outcomes post treatment could be made), or at assessments conducted 4 and 17 days post treatment. Thus, leaving 70% of the plot untreated did not result in control failure or resurgence of slug populations in this case. Care must be taken when interpreting this result, however, due to the very low slug populations present and more extensive testing and verification of the procedure is required before definitive conclusions can be drawn.

Within these significant limitations, farmer concerns regarding the level of control achieved with patch treatment when compared to treatment of a whole crop were considered in a comparative trial. The area of crop left untreated in this experiment was larger than the mean percentage areas harbouring higher slug numbers that have been calculated for other fields studied in this project (Petrovskaya *et al.*, 2020), but post treatment assessments still revealed no indication of population resurgence/recolonization of treated areas within the damage window for the crop.

Cost-benefit considerations indicate that the data generated by soil assessments for other husbandry purposes can be re-used, with spatio-temporal stability allowing considerable flexibility in the timing of such assessments, obviating concerns expressed by farmers and agronomists. Overall, the new procedure results in small savings in the costs of variable inputs. However, a major benefit of the approach is the potential for substantially reduced pesticide usage for slug control with associated improvements to sustainable production of major arable crops. Although a monetary value for the contribution to sustainability can be calculated, this is an area of specialist expertise and so has not been incorporated into the cost-benefit analysis (Eftec, 2010; Johanssen, 1990).

5.7 Future development priorities

The prototype procedure for patch treatment of slug infestations in arable crops using commercial products which has been, developed in this programme of study was based on extensive field data, experimental work and industry consultation/guidance. Before it can be released for practical use, however, wider testing and verification of the system is required in close consultation with industry representatives. The testing should include:

1. “Challenge testing” of both the full procedure, and main individual components of the procedure, in fields with higher slug densities (using a minimum of 1 ha plot size). The plots should also be used as demonstration plots to seek end user/industry opinion and advice on all aspects.
2. Wide-spread whole-field validation of the procedure in all major arable regions of the UK, using commercial soil mapping procedures, equipment and software, and the precision application technology available on commercial farms. Fields should be pre-screened to ensure a satisfactory range of slug population sizes are investigated.
3. Experimental comparison of the use of soil texture assessments, or electroconductivity scans, at a wider range of field sites in all major crop growing regions of the country, in order to confirm its use as a proxy in the protype procedure.
4. If the validation experiments conducted under points 1 and 2 indicate it is required, data collected should be used to further refine the model predicting slug patch location.

5. Using data collected from points 1-4 above, final adjustment and optimisation of the prototype procedure should be undertaken before it is considered for commercial release.

5.8 Published papers emerging from the project to date

The following papers have been published during the life of this project; two more peer reviewed papers are in preparation; a third paper is currently under discussion between EF and KFAW:

Ellis, J.; Petrovskaya, N.; Forbes, E.; Walters, K.F.A.; Petrovskii, S. (2020). Movement Patterns of the Gray Field Slug (*Deroceras reticulatum*) in an Arable Field. *Nature Sci. Rep*. 2020 doi.org/10.1038/s41598-020-74643-3

Forbes, E.; Back, M.A.; Brooks, A.; Petrovskaya, N.B.; Petrovskii, S.V.; Pope, T.W.; Walters, K.F.A. (2020). Locomotor behaviour promotes stability of the patchy distribution of slugs in arable fields: Tracking the movement of individual *Deroceras reticulatum*. *Pest Manag. Sci*., **76**, 2944–2952.

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