Comparison of slug population dynamics at five sites in the UK

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ABSTRACT

Slugs are major agricultural pests both in the UK and throughout Europe. Slug population dynamics are highly dependent on the weather and consequently future climate change may alter their numbers and distribution. These changes can be forecast using climate change scenarios and modelling techniques to provide valuable information for future management strategies. The relative importance of different environmental variables will be assessed using data from five sites across the UK and an existing individual-based model of slug population dynamics. Climatic data from each of the sites will be run through the model and the resulting populations compared. Temperature and rainfall data can then be isolated for each site and run with a standard set of values. The results of these simulations will be discussed with a view to furthering the understanding of how temperature and rainfall affect slug populations and consequently how changes in climate may affect abundance and invasiveness of pest species throughout Europe.

INTRODUCTION

Slugs can cause extensive damage to crops including damage to seeds or seedlings, destruction of stems and growing points, increased susceptibility to fungal attack and the reduction of leaf surface area. Cosmetic damage through the presence of mucus trails or faeces, reduction of yield and slowing down of crop development can also cause economic losses (Bohan, *et al*, 2002). Slug behaviour and activity are highly dependent on weather conditions, as slugs must maintain a humid micro-environment due to their permeable integument. This is often achieved through altered behaviour, for example huddling and shelter seeking (Prior, *et al*, 1983). Studies have shown that warm, wet conditions (Rollo, 1982) are optimal for slug activity, and it is these weather conditions which frequently result in the most severe damage, particularly in the spring and autumn (Mellanby, 1961). Short-term weather changes can cause severe local damage, but longer term weather changes will also have implications for the population as a whole and for management strategies.

Given that weather is an important factor in determining slug activity, future changes in climate may strongly influence the degree of damage caused by slugs. There is already some evidence in Europe of increased slug damage resulting from expanding ranges of invasive species (Grimm & Schaumberger, 2002). The range of pest slugs is also believed to be expanding across Britain. *Deroceras reticulatum* (Müller) is one such pest species and is believed to be causing increasing problems, as are two other species, *Arion lusitanicus* Mabille and *Boetgerilla pallens* Simroth which have invaded Europe in the colder drier east over the past 50 years. Global mean surface air temperature is predicted to increase by 1-3.5°C by 2100 relative to 1990 (Cannon, 1998). Although temperature changes will not be even, and impacts will be greater at lower latitudes, predicted increases may favour pest slug species causing increased damage problems. Predictions of changes in population dynamics would be useful, not only to minimise damage, but also to enable the efficient application of molluscicides, reducing costs and benefiting the environment.

Here we use an individual based model of slug population dynamics to investigate range expansion and invasion of slug species with climate change. The model uses rainfall and temperature data to predict changes in the numbers of adults, eggs and juveniles in the population. We evaluate the influence of different temperatures and rainfall on the size and dynamics of slug populations.

METHODS

The individual based model of slug population dynamics had previously been extensively validated against *D. reticulatum* data observed at Letcombe Weed Research Organisation Laboratory. It was also validated against slug abundance data from Long Ashton Research Station, observed in the field using soil sampling.

Five sites throughout the UK were chosen for this study; Okehampton, Letcombe, Glasgow Airport, Belfast and Stornoway. Temperature and rainfall data for each site were summarised by using monthly. The model was run for each site ten times for a two year period and the resulting populations compared.

Differences in temperature and rainfall patterns were also investigated. To do this the model was run ten times using rainfall data for each site and temperature data from Okehampton as a standard and *vice versa*. Resulting data were plotted on a graph showing average population sizes for each site. Data were also plotted on a logarithmic scale for each combination of weather to show differences in the pattern of population change. Given the results, temperature and rainfall for all the sites were compared between 9/1/86 - 30/4/86 and the model then run ten times using temperature data from Glasgow and rainfall data from Stornoway. Standard deviations for these time periods were also calculated for each site.

RESULTS

Validation of the results against the Long Ashton data revealed that the model produces a similar pattern of slug abundance compared with those observed by trapping and soil sampling. Figures 1 and 2 average temperature and rainfall respectively.

In the first year, Stornoway had the largest total population followed by Glasgow with the other sites having similar populations (Figure 3). All sites were similar in the second year.

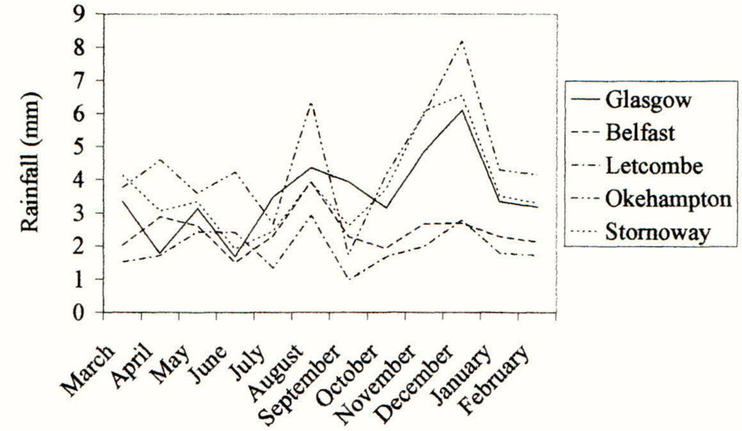

Figure 1. Running two year average monthly rainfall between March 1985 and February 1987.

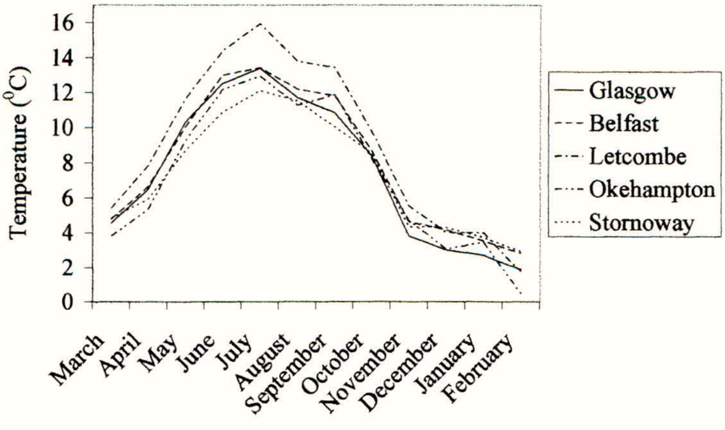

Figure 2. Running two year average monthly temperature between March 1985 and February

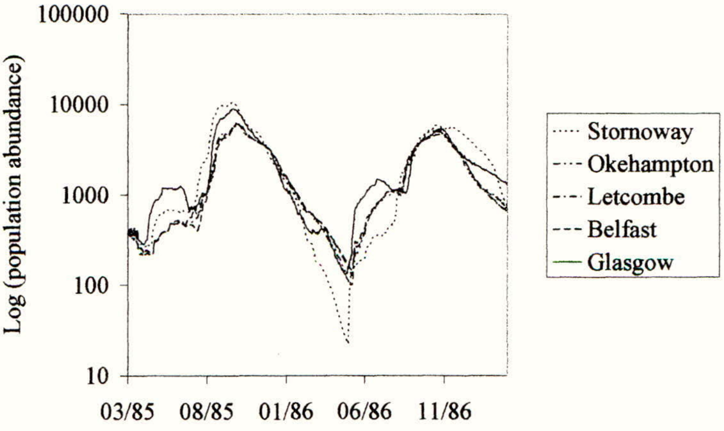

Figure 3. Slug abundance when each site's own temperature and rainfall were modelled.

When count data were plotted on a log scale, the Stornoway population showed a slightly larger population decline between 9/1/86 and 30/4/86 in comparison with the other sites. When weather data were compared, a period of dry weather at Stornoway was eight days longer than at any other site. The standard deviations of the data for each site show that Stornoway data are no more variable than other sites (Figure 4). Stornoway's rainfall data were therefore also run with Glasgow's temperature data. When rainfall data were run for each site with the standard Okehampton temperature data, Stornoway had the largest populations in both years, followed by Glasgow. Belfast and Okehampton had the next largest populations, with Letcombe having the lowest population. A decline in abundance was also seen at Stornoway between 9/1/86-30/4/86, although it was relatively smaller than that seen in the Stornoway-only simulations (Figure 5).

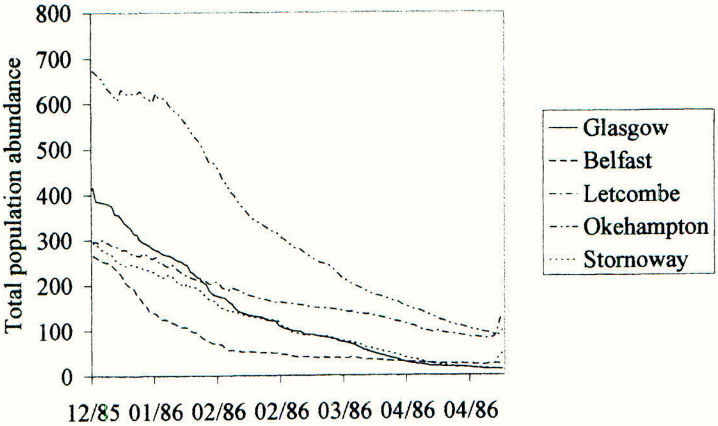

Figure 4. Graph showing the standard deviation of the total populations for each site.

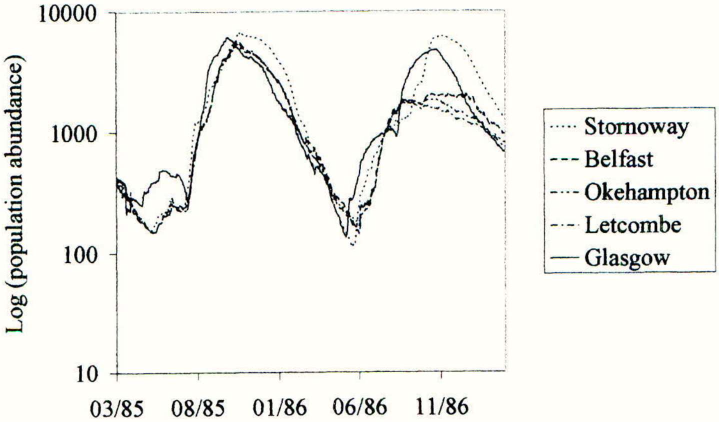

Figure 5. Graph showing total slug populations when rainfall was investigated.

When temperature data were run with standard Okehampton rainfall data, the simulations showed that Okehampton and Letcombe had the most abundant slug populations. Belfast and Glasgow had similar, intermediate sized, populations, and Stornoway had the smallest population (Figure 6).

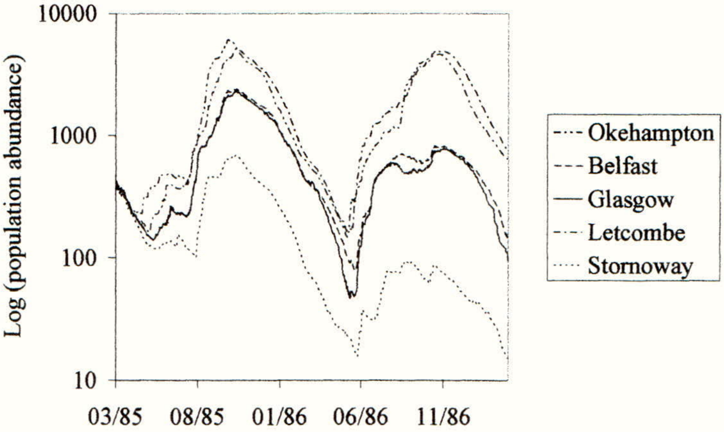

Figure 6. Graph showing total slug populations when temperature was investigated.

DISCUSSION

The successful validation of the model against data from two sites provided considerable support for the model. Initial model runs showed that Stornoway had large slug populations. Stornoway is at sea level and the high abundance may be because there are few days of freezing weather: this may mean that the population was less affected by extreme weather conditions. Slug abundance at Letcombe and Okehampton were similar. Although weatherdata for each site show that Okehampton is wetter and cooler than Letcombe, patterns of rainfall and temperature peak at the same times of year at both sites. This could imply that these factors are important in determining slug population abundance. The results also showed a large fall in abundance at Stornoway in mid-January 1986 until the end of April that year. Differences between the temperature and rainfall values at Stornoway and all other sites were therefore compared, and showed that Stornoway had an extra eight days of dry weather. This suggests that extended periods of dry weather could cause larger declines in abundance. When soil moisture content falls below 30% there is a significant decrease in slug activity (Young, 1991), this would lead to reduced growth and reproduction in the population as a whole and cause the decreases in numbers seen. It would therefore be expected that when rainfall data were isolated and run against standard temperature, the same decline would be seen.

The isolated rainfall data showed a drop in slug abundance at Stornoway in the same time period as before. However, in contrast to what was expected, the drop in numbers was not as large as that seen when Stornoway's own temperature data were used. One explanation for this is that the standard Okehampton temperature data were more favourable and therefore may have reduced the negative effects of the dry period. To test this, Stornoway's rainfall data were also run with Glasgow's which are more similar than Okehampton's. The graphs again showed a drop in numbers during the same time period, supporting the idea that longer periods of dry weather cause bigger crashes in the population and also that the extent to which abundance is reduced is also influenced by the temperature conditions. When the rainfall data for each site were run with standard temperature values, similar patterns of population numbers were seen to those observed when the weather data were run without a standard. Stornoway had the largest populations, followed by Glasgow, and then Letcombe, Belfast and

Okehampton which all had similar population sizes. One difference was that the peak population sizes for Stornoway and Glasgow were larger in the second year when temperature was isolated. This may indicate that rainfall was more influential in 1986 at these sites.

Stornoway had the lowest average summer temperatures (between May and October) and the smallest populations when the effects of temperature were isolated. This may indicate that summer temperature is the key for increasing slug populations. In the model the optimal temperatures for eggs, juveniles and adults were 16, 15 and 15 ^{0}C respectively. Monthly average temperatures at Stornoway were always cooler than this; slug reproduction was therefore always sub-optimal. Letcombe, in contrast, was on average, warmer than 15 ^{0}C from June until August and therefore had periods of time in June and August when slugs were at their optimum temperature and correspondingly had relatively large populations. Average temperature appears to have an effect on the overall population size, as the population followed a similar pattern to temperature change (figures 2 & 3), particularly in 1985. A similar pattern was seen in 1986, but was slightly delayed, presumably because the Figure 2 represents an average over two years. Temperature (Figure 6) also appears to affect population size more strongly than rainfall (Figure 5). From these results the likely effects of future climate changes may be forecasted. If the climate becomes dryer, for longer periods of time, the slug population may decrease. Similarly if the climate becomes either significantly warmer or colder, inhibiting slug activity, population numbers may also decrease.

In conclusion, the model was validated against long-term soil sampling data from Long Ashton and Letcombe. It appeared that the longer the period of dry weather the larger the reduction in slug population numbers. Temperature changes were important in determining total population size, whereas growth and decline were determined by both adverse rainfall and temperature. Temperature influenced overall slug abundance more strongly than rainfall.

ACKNOWLEDGEMENTS

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Slugs and nematodes in a fighting arena – individual based models of parasitism

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ABSTRACT

Slugs are one of the most important pests in agricultural and horticultural crops in the UK and Europe. The slug-parasitic nematode biocontrol agent, *Phasmarhabditis hermaphrodita*, is available commercially in the UK. We have developed an individual based model to describe the temporal and spatial dynamics of slug and nematode populations and their interaction. The model depicts a simulated field using a grid of cells. The carrying capacity of each cell permits the elaboration of density-dependent slug behaviour, and allows the integration of small-scale interaction studies into wider spatial dynamics. The dispersal, in space, and density changes of the slug population can be traced across the simulated field, following nematode application. In this modelling study scenarios for individual-slug state-dependent egg-hatching, development, oviposition, growth, mortality, and dispersal were constructed and investigated. The model proves to be a powerful tool to observe changes in control success for different scenarios of nematode application.

INTRODUCTION

Slug damage is a considerable cost to the agricultural and horticultural industry in the UK and Europe. The field slug, *Deroceras reticulatum* (Müller), is the most important pest slug species in UK and the study pest population for the modelling study in this paper. *D. reticulatum* can reduce the vigour of crops by killing seeds or seedlings, by destroying stems or growing points and by reducing plant leaf area. This feeding may slow down crop development and/or reduce yield. In other crops, the harvest may be devalued by cosmetic damage, due to the presence of slug feeding, mucus trails, faeces or the slugs themselves. Slug feeding may also initiate mould growth or rotting. *D. reticulatum* can oviposit through the year whenever the conditions are suitable leading to multi generations in one year. Adult *D. reticulatum* are out-crossing hermaphrodites.

Research into the natural enemies of slugs aims to improve current techniques to control them biologically. One such natural enemy is the bacterial feeding nematode, *Phasmarhabditis hermaphrodita*, discovered at Long Ashton Research Station (Wilson *et al.*, 1993). These nematodes have been developed as a biocontrol agent by a commercial company (MicroBio Ltd, now Becker Underwood Ltd) in collaboration with Long Ashton Research Station and have been available for home-garden use since 1994. Due to the high cost of production and a limited shelf life for these nematodes, developing an effective and economical way of controlling slugs with nematodes is essential.

Mathematical modelling approaches have been used to describe the growth of slug populations using deterministic (Schley & Bees, 2002; 2003) and individual based models (Shirley, *et al.*, 2001). This paper introduces an individual based model to investigate how biocontrol approaches, using *P. hermaphrodita*, may be optimised.

MATERIALS AND METHODS

A deterministic model was previously developed to describe the growth of a slug population to calibrate model parameters in the field using observed environmental data and field slug sample data for the period of one year between 1 March 1985 and the 28 February 1986. This simple model of slug population dynamics corroborated an expected strong relationship between slug activity and environmental conditions. The set of calibrated parameters was then used to simulate slug population dynamics against long-term environmental data for validation with observed slug data for the next two and half years from the same field (between 1 March 1986 and 8 September 1988). Although the simulation results were unable to explain the large drop in slug abundance that occurred in 1986, they were able to show the trend of annual slug population peaks during the simulation period. This work also illustrated the difference between experimental data in the laboratory and what happened in the field and strongly supported the suggestion that laboratory studies need to be extrapolated to the field with great care (see South 1992).

The *D. reticulatum* individual based model is an object-oriented model developed to describe the temporal, stochastic and spatial dynamics of slugs and nematodes, and their interactions. This simulation program has a Windows interface, so that many ecologists may manipulate the parameter set and environmental conditions to observe the effects of changes on slug population dynamics. There are three categories of objects included in the model: 1) the slug population, 2) the nematode population and 3) the geographical cells where slugs and nematodes live and encounter each other.

The slug population is weight-dependent and divided into four distinct life stages: 1) eggs, 2) neonates, 3) juveniles, and 4) adults. The non-egg stages are distinguished by their current weight with slugs weighing 0-10 mg being neonates, 11-100 mg being juveniles and heavier than 100 mg being adults. Slugs have a list of individual information including slug number, species, life status, age, weight, location (x, y co-ordinates), hatching time-delay, oviposition recovery time-delay, weight group, nematode infection matter and infection period. All three stages gain weight according to a given mathematical formula and their current weight. Only juveniles and adults are assumed to be mobile and adults only are able to reproduce. Most of the parameters included in the model are set up as a mixture of weight and environment-dependent functions. A concept of threshold conditions, from day-degree models (Powers *et al*, 2003), has been adopted because both slugs and nematodes are inactive in low and high temperatures and dry conditions. The mortality rates are unique to each life stage. The maximal distance slugs move is dependent on their weight and location. There are two time-delays employed in the model for egg development (hatching) and oviposition recovery period (after the previous oviposition). These time-delays get daily input from weighted sine functions of temperature and rainfall and, when they reach a pre-determined time-delay, eggs may hatch or adult slugs may lay eggs. Slugs visit a cell in the virtual field and damage one unit every day. This crop damage can be an important measure of slug control success in different field designs. Stochastic processes are included in all procedures of the slug population model.

The nematode population appears when applied to the field. The user decides the timing of the spray, the method of spray (random or other methods), the number of nematodes sprayed, life expectancies (minimum and maximum), the infection rate when one slug and one nematode meet, contact rate and the number of nematodes produced by an infected adult slug. In contrast to slugs, the number of nematodes sprayed (for example 300,000/m^2) is too many to simulate individually in the virtual field even in the IBM (for a personal computer). A deterministic procedure is employed here as the product of survival rate and the number of nematodes in the cell decided the survived nematodes for the current day. Only juvenile and adult slugs are assumed to be infected by nematodes but this can be easily changed to other mechanisms. Infected juvenile slugs are assumed to reproduce nematodes at half the rate of adult slugs. The mortality rates of nematodes are strongly related to the changes of environmental conditions especially rainfall and temperature. The influence of rainfall is set up as yes (1) or no (0), i.e. whether there was rain, not the amount of rainfall. The temperature gets the same sine function as slugs have and these two functions get weighted and added to decide the mortality rate of nematodes for the current day.

The virtual field is divided into a number of spatially explicit geographical cells, with the magnitude of the field and the number of cells being determined by the user prior to simulation. Each individual cell has a suite of priorities, including the carrying capacity, slug damage (a number of slug visits), crop variety, numbers of slugs (eggs, neonates, juveniles, adults, infected juveniles and infected adults) and the number of nematodes. The crop variety is currently divided into three crops: a main crop, an attractant crop and a repellent crop, which allow different cropping regimes to be investigated. Consequently, attractant and repellent crops need not be used for simulation. The attractant crop is used to attract slugs from the main crop, to reduce the slug damage to the main crop, and slugs are assumed to be unable to survive in the repellent crops. Main and attractant crops can become repellent should the carrying capacity of the cell exceed the damage threshold.

The boundary of the virtual field is closed. When slugs reach the boundary they are forced to move to an adjacent cell. This criterion can be changed to other boundary scenarios such as reflection, where slugs bounce back from the boundary, opposite mirror, where slugs re-enter the field on the opposite side from which they left, and disposal, where slugs leaving the field are removed from the simulation.

RESULTS

The *D. reticulatum* data were taken from a long-term experiment at the Northfield site of the Agricultural and Food Research Council Letcombe Laboratory, in the Vale of the White Horse, Oxfordshire, England (OS Grid reference SU 394212). Soil samples were taken from each of the 16 direct-drilled subplots at approximately monthly intervals, between autumn 1982 and autumn 1988, with the number and individual weights and species of slugs being recorded (Glen *et al.*, 1984; Christian *et al.*, 1999). The data used for the validation of the individual based model is averaged for the number of slugs per square meter. Parameter values to run the simulation of the individual based model were extrapolated from the literature. The field is designed to be a monocrop of only a main crop. Nematodes were simulated as being sprayed with a uniform distribution at 300,000/m^2 (the recommended dose). Twenty replicate simulations for nematodes and slugs and for slugs alone were run to compare the effects of the nematode application. Nematode application was simulated on the second day (2 March 1985). The life expectancies of nematodes are assumed to be a maximum of 60 days and a minimum of 3 days, depending on environmental conditions. Infected adult slugs were assumed to produce 100 nematodes and juveniles to produce 50. The sample data and simulation results of slug population without nematode application are presented for the period between 1 March 1985 and 2 April 1988 (Figure 1).

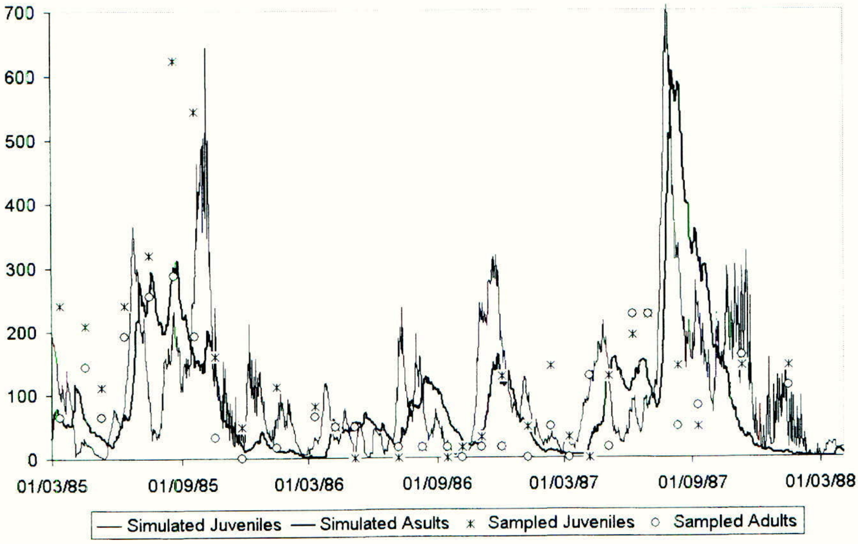

Figure 1. A comparison between slug data sampled from field and simulation results without nematode application for the period between 1 March 1985 and 2 April 1988

Only adult and juvenile slugs are presented for comparison. Simulation results after the application of nematodes on the second day of the simulation period are presented in Figure 2.

Simulation of the individual based model with nematode applications affected the slug population compared to the previous results without the nematode application. The infected slug population increased quickly with, as a consequence, a reduction of susceptible juveniles and adults after the nematode application, then infected slugs vanished within the field 42 days after application (11 April onwards). The abundance of susceptible juveniles and adults was suppressed and this shifted the peak of the susceptible slug population to later in the season (between August and November 1985). This peak, in the presence of nematodes, occurred after harvest and it indicates more practical benefits of the nematode application for crops that are susceptible to damage close to harvest.

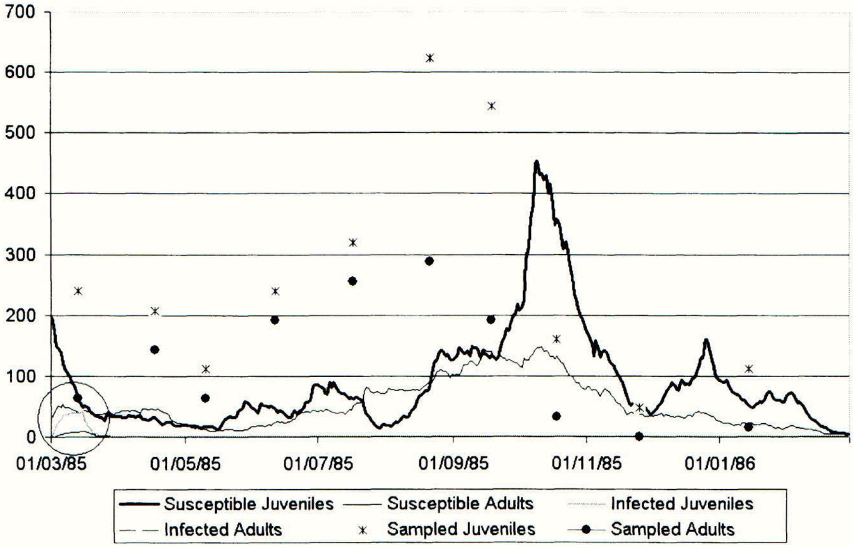

Figure 2. Slug sample data and simulation results of the slug population after the nematode spray on the second day of the simulation. (nematode and infected slug populations in the circle on the left bottom corner.)

By comparing simulated crop damage based on the number of slug visits in the geographical units, the nematode application has a significant effect. The IBM ran 20 replicate simulations for an appropriate number of replications giving standard errors within 5% of the crop damage estimates. The crop damage caused by slugs without a nematode application was estimated at 30.34 per unit, with a confidence interval (29.19, 31.49), but was 22.12 per unit with a nematode application with a confidence interval (20.26, 23.97) when the nematode was sprayed on 2 March. Where the number of nematodes produced by an infected adult slug was altered from 1000 to 100, no significant change in dynamics or damage was observed. This finding implied the importance of the initial number of slugs prior to the simulation on the population changes during the year. The comparison between sample data and simulation results provided strong evidence of the validation and power of the individual based model of the slug and nematode populations and their interaction. Simulation results on the sensitivity of the few parameters presented in this paper would be not only be useful for determining more efficient methods of controlling slugs with nematodes but also a great stimulant to slug ecologists to recognise the most important parameters in slug control studies.

The Windows interface program of the individual based model of slug and nematode interactions developed for this study is flexible, allowing users to modify existing parameter values and their mathematical functions, with better understanding, in order to observe the sensitivity of the model to such changes. An individual based model can also be used to investigate behaviour, such as slug avoidance of nematodes. This flexibility allows slug ecologists and agriculturists to observe the possible effects of treatments suggested by research and, for the purpose of the biological control of such pests, possible effects of introducing new species into existing ecosystems. An individual based model is a useful tool to integrate small scale studies of slug ecology into large-scale field experiments. Modelling techniques are appropriate tools to evaluate the effectiveness of control methods prior to field experiments or practical application.

Further studies of parameter changes, including nematode dose, geographical designs of nematode applications, multiple applications along with their effects on slug control are planned for the future.

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Weeds or wheat? Do weeds have the potential to reduce slug damage to winter wheat?

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ABSTRACT

The potential for five common weeds of arable fields to reduce the grazing of field slugs (*Deroceras reticulatum*) on wheat seedlings was assessed. Slugs exhibited preferences for particular weeds and the presence of some weeds and their density had a significant effect on the damage to wheat seedlings by slugs over 72h. The potential role for managing weed populations in the autumn to reduce the damage to wheat seedlings is discussed, particularly in relation to minimum and no tillage systems.

INTRODUCTION

Slugs are often a perennial problem in arable crops, particularly winter wheat, where slug grazing of seed and the emerging leaves can hamper the establishment of the crop. The costs of slug control in UK cereal crops in terms of use of molluscicides is estimated to be in the region of £4-5 million a year (Oakley & Young, 2000), although costs may vary depending on the slug populations in any given season. The adoption of integrated crop management (ICM) and minimum or no-tillage systems by UK growers has led in many cases to an increased risk of slug damage in crops (Voss, *et al.* 1998; Andersen, 1999). There is evidence that minimum tillage systems do build up populations of slug predators such as carabid beetles (Symondson, *et al.* 1996; Kromp, 1999), but growers are still concerned about the potential for exacerbating the problems of slug damage to autumn-sown crops, particularly winter wheat.

Adoption of ICM and minimum tillage has altered the way that many growers manage weed problems in their crops: The drive to reduce herbicide inputs can make some weeds more problematic, while minimum tillage can reduce some weed species to some extent. In recent years, there have been several studies on the palatability of weeds to slugs (Cook, *et al.* 1996, 1997; Frank & Barone, 1999; Frank & Friedli, 1999; Kozlowski & Kozlowska, 2000) and distinct feeding preferences for weed species have been determined for a range of common weeds.

The research outlined in this report describes results obtained when looking at the feeding preferences of field slugs (*Deroceras reticulatum* (Müller)) in choice tests between five different weed species and winter wheat seedlings, and the impact that different weed densities have on the damage to winter wheat.

MATERIALS AND METHODS

Five weed species were used in the feeding tests, and were chosen based on previous studies (Cook, *et al.*, 1996, 1997; Frank & Friedli, 1999) and associations of slugs and weeds noted in crops (Davies, *et al.*, 1997): winter oilseed rape (*Brassica napus*), dandelion (*Taraxacum officinale*), shepherds purse (*Capsella bursa-pastoris*), field-speedwell (*Veronica persica*), and annual meadow grass (*Poa annua*). The wheat cultivar used was Riband, chosen on the strength of its broad commercial appeal, and palatability to slugs (Evans & Spaull, 1995).

Adult field slugs, weighing between 0.4-0.9 g, were collected from a grass field and stored in a clear plastic container at a temperature of approx. 12-18°C. The base of the container was covered with a 1 cm deep layer of soil. During storage the slugs were fed a daily diet of lettuce and carrot.

Wheat seeds and weed seeds of the varieties to be tested were sown in separate seed trays containing John Innes No. 2 compost. The trays were kept in a glasshouse at a temperature of 15-20^{0}C, 8:16 hour light:dark photoperiod. The weed plants were at the two to three leaf stage during the feeding experiments. Wheat seeds were transplanted into seed trays (15 x 21cm) in two rows of five plants. The medium was John Innes No. 2 compost. Each weed variety was transplanted into these trays (once the wheat plants had two leaves) at three different densities of planting, 15 plants/tray, 10 plants/tray and 5 plants/tray. This is equivalent to weed densities of 477 plants/m^2, 318 plants/m^2 and 159 plants/m^2 respectively. The wheat density was constant at 318 plants/m^2. The position of the weed plants was randomly determined. Three replicates were prepared for each population density. Three trays, containing solely wheat, were prepared as a control.

The slugs were starved in isolation for 24 hours prior to the experiments. One adult field slug was placed in the middle of each tray. The trays were enclosed with clear plastic lids, ventilated to allow the circulation of air. The experiment was conducted in a laboratory at a temperature of 15°C with a 12 hour photoperiod. The slugs remained in the trial trays for a period of 72 hours. Damage to both weed and wheat plants was visually assessed every 24 hours on a scale of 0 to 5 (0 representing an undamaged plant and 5 representing total destruction of the plant), in order to record the incidence and extent of feeding (although only incidence results are reported here). After 72 hours, below-ground damage to wheat seed was assessed on a visual scale of 1-5.

Slug feeding preferences between winter wheat and weeds

Data from the trays in which wheat and weeds were planted at equal densities (wheat and weeds at 318 plants/m^2) were used for this assessment. Analysis of variance was carried out to determine any differences between slug damage to wheat seedlings when weeds were present or absent.

Impact of weed density upon wheat damage

The damage to wheat seedlings (and weeds) at different weed densities was determined after 72h. Differences in wheat damage at different weed densities were determined using analysis of variance.

RESULTS

Slug feeding preferences

When wheat seedlings were available to slugs in a no choice situation at a density of 318 plants/m^2, a third of seedlings exhibited feeding damage after 72 h. No damage to the seed was detected in any of the trials.

When given a choice between wheat seedlings and weeds (both wheat and weeds at a density of 318 plants/m^2), slugs preferred the weed plants to wheat for all weeds tested ($P < 0.05$), except for annual meadow grass, where wheat was significantly preferred (Table 1).

Table 1. Mean % of slug damaged plants (± SE) after 72h when weeds and wheat were planted at the same density – 318 weed and wheat plants/m^2 (n=3)

Weed species	% of wheat plants damaged	% of weed plants damaged
Winter oilseed rape	6.7 ± 3.3	23.3 ± 3.3
Field speedwell	16.7 ± 3.3	30 ± 0
Annual meadow grass	23.3 ± 3.3	3.3 ± 3.3
Shepherds purse	13.3 ± 3.3	50 ± 5.8
Dandelion	10 ± 5.8	40 ± 5.8

Weed density and slug damage on wheat

When dandelion and winter oilseed rape were presented to slugs at different densities with a fixed density (318 plants/m^2) of wheat seedlings, there was a significant reduction in wheat damage after 72h at each weed density (Figure 1), except for oilseed rape at the lowest weed density of 159 plants/m^2. The higher the weed density, the greater the reduction in wheat plants damaged (Figure 1).

For the other weed species, except for annual meadow grass, there was also a significant reduction in the percentage of wheat seedlings damaged by slugs at each of the weed densities ($P < 0.05$), although wheat damage tended to increase with increasing weed density (Figure 2).

DISCUSSION

Slugs can feed on a wide range of plants as well as those being grown as food crops, but distinct feeding preferences occur within slugs, and between different slug species, for the plants they encounter in a field situation (Cook, *et al.*, 1996, 1997; Frank & Barone, 1999; Frank & Friedli, 1999; Kozlowski & Kozlowska, 2000). The need for adequate weed control in order to prevent weed competition with the maincrop encourages slugs to feed on the crop, as alternative food sources are significantly reduced. With growers moving towards sustainable agricultural systems, and adopting ICM and minimum tillage techniques, weed populations within crops, and consequently alternative food for slugs, tend to be larger. It is accepted that slug populations tend to increase in minimum- or no-tillage systems (Voss, *et*