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RESEARCH ARTICLE

Relative efficacy of biological control and cultural management for control of mollusc pests in cool climate vineyards

Matt Egleton, Zoltan Erdos, Ben Raymond and Andrew C. Matthews

Centre for Ecology and Conservation, Biosciences, College of Life and Environmental Sciences, University of Exeter, Exeter, UK

ABSTRACT

Restrictions on the use of synthetic molluscicides highlight the importance of developing alternative control methods. Nevertheless, biocontrol agents can be costlier and less effective than synthetic counterparts. One means of increasing the efficacy of population suppression is to combine inundative biological control with habitat management to reduce population growth of target pests. Vineyards in the cool, wet climate of western England can suffer from outbreak densities of mollusc pests that damage expanding shoots, developing grapes and promote the transmission of fungal pathogens. In this study we combined the biocontrol agent Nemaslug – *Phasmarhabditis hermaphrodita* (Schneider) – with a simple habitat management approach (regular mowing) to suppress mollusc pests in vineyards in South Western England. Two sites were treated with NemaSlug and or mowing in a factorial design in early spring coinciding with bud burst and the start of mollusc growth and feeding. Mowing was effective management and resulted in the reduction of slug and snail populations and significantly less damaged vines. Nemaslug did not reduce slug numbers overall but did reduce bud damage, snail numbers and lowered the proportion of susceptible *Deroceras* spp in treated plots. However, effect sizes of nematode biocontrol were small, potentially because this product could not be applied to bare soil. Management practice for cool climate vineyards varies considerably from site to site. This study shows the value of simple habitat management for controlling a novel target and emphasises how consideration of pest biology can lead to effective alternatives.

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Nematodes; *Phasmarhabditis hermaphrodita*; grapevine; non-chemical control; slugs and snails

Introduction

Slugs and snails are economically important pests of a variety of crops worldwide causing direct damage via feeding and contaminating surfaces with excreted mucus and faeces (Barker, 2002). Mollusc pests are especially challenging for agricultural industries in mild, damp climates such as the UK (South, 1992). Management of these pests heavily

CONTACT Ben Raymond b.raymond@exeter.ac.uk Centre for Ecology and Conservation, University of Exeter Penryn Campus, Treliever Road, Penryn, Cornwall TR10 9FE, UK

rely on ecologically damaging and environmentally persistent chemicals (Henderson & Triesbskorn, 2002). The most commonly used molluscicide substances are metaldehyde, iron-III-phosphate and carbamate compounds formulated as pellets that attract and kill molluscs on contact (Bailey, 2002). Synthetic pesticides are coming under increased scrutiny for their negative health and environmental impacts such as their role in the decline of wildlife (Kim et al., 2017; Mancini et al., 2019). While being effective pest control agents, these substances can be toxic to vertebrates, including humans, pets and other mammals (De Roma et al., 2017; De Roma et al., 2018) and to non-target and beneficial invertebrates including earthworms and carabids (Cardoso et al., 2015; Purvis & Bannon, 1992; Rae et al., 2009b; Santos et al., 2010). Furthermore, a report by Castle et al. (2017) on metaldehyde entering drinking water sources details the potential effect on public health and the cost of removal for water companies. Concerns over the negative impacts of metaldehyde prompted its ban for outdoor use in the UK from spring 2022. The high development and registration costs of new synthetic pesticides and the rapid emergence of pest resistance makes biological control an attractive alternative for pest management (Glare et al., 2012).

Biological control presents a great opportunity for movement towards a more sustainable agriculture (Naranjo et al., 2015). The molluscicidal nematode, *Phasmarhabditis hermaphrodita*, parasitises many terrestrial mollusc pest species reducing crop damage by inhibiting feeding or killing the host (Glen & Wilson, 1997; Rae et al., 2007; Wilson et al., 1993). Nematodes are attracted to the mucus and faeces of the molluscs, particularly that of *Deroceras reticulatum* (Hapca et al., 2007). Infective dauer larvae of the nematodes penetrate the molluscs beneath the mantle, develop into self-fertilising hermaphrodites and start reproducing (Wilson et al., 1993). Host death occurs 4–21 days after infection depending on the infective dose and temperature (Tan & Grewal, 2001). An important characteristic of biological control based on *P. hermaphrodita* is their host specificity and lack of significant ecological side effects (Ehlers, 2003). Previous evidence suggests that *P. hermaphrodita* may utilise earthworms for transportation (MacMillan et al., 2009), but does not parasitise them, even when the earthworm is injured (De Nardo, 2004). Studies by Wilson et al. (2000) and Iglesias et al. (2003) has also shown that *P. hermaphrodita* does not pose a threat to non-target molluscs and invertebrates. The nematode migrate no further than a few centimetres to find a suitable host so effects of applications on non-targets are spatially restricted (Wilson et al., 2000). *P. hermaphrodita* has been formulated into the biological control product NemaSlug and successfully used as an inundative biocontrol agent to protect a range of crops against mollusc damage (Ester, Huiting, et al., 2003; Ester, Van Rozen, et al., 2003; Glen, Wiltshire, et al., 2000; Wilson et al., 1995; Wilson, Glen, George, et al., 1994). Recently developed application techniques have helped reduce application costs (Hass et al., 2010; Rae et al., 2007; Rae et al., 2009b).

The introduction of cold-climate grape cultivars (Jones & McManus, 2017) led to the emergence of cool-climate viticulture areas and the expansion of wine grape industry into Denmark, England and southern Sweden (Fraga et al., 2013; Nesbitt et al., 2018). Areas with cool temperature and high humidity can face significant mollusc damage if control through conventional synthetic chemicals is reduced. With synthetic molluscicides coming under increased scrutiny for their environmental impact, biocontrol nematodes have great potential in filling the void in the pest control market. There are currently no studies available of NemaSlug trials in vineyards, indicating a novel application of the product.

We supplemented conventional inundative treatment in two ways to try and improve efficacy. First, we incorporated refuge traps as an addition to an integrated pest management system combined with NemaSlug. Local *P. hermaphrodita* application may cause molluscs to flee nematode treated soils and potentially reduce mortality (Grewal et al., 2001; Wilson et al., 1999). The concept of a refuge trap is that any molluscs dispersing away from treated areas will congregate in refuges where they can be killed by baits or molluscicides and improve long-term control at reduced cost (Grewal et al., 2001). Second, we combined Nemaslug application with a mowing treatment designed to reduce habitat suitability for molluscs by reducing humidity and forage. Habitat management can also be an effective supporting tool in reducing pest populations (Pickett & Bugg, 1998). A common habitat management method for slugs in field crops is tillage (Le Gall & Tooker, 2017). The use of ploughing and other tilling practices are often used to incorporate nitrogen and remove suppressing weeds. However, this creates monoculture, removing the host species of natural enemies of pests and other beneficial invertebrates (Sharley et al., 2008). Due to risk of damage to vines and their root systems during deep tillage vineyards are left with the option of reduced tillage in inter-rows or the use of a plant cover (Kazakou et al., 2016). Cover crops can be temporary or permanent, spontaneous or sown. Cover crops or weeds as an alternative food source could potentially limit crop damage by slugs and snails on some crop species (Cook et al., 1997; Landis et al., 2000). However, such cover crops can also shelter grapevine pests (Hanna et al., 2003) and increase the likelihood of pest attack (Wermelinger et al., 1992). Grass cover can host soil-borne pathogens and nematodes which could lead to grapevine damage (Castillo et al., 2008). This study aims to assess the efficacy of NemaSlug in controlling mollusc pests on grapevines in Cornish vineyards. Conventionally, NemaSlug is applied to bare soil, however the presence of vegetation under vines meant that we applied Nemaslug to vegetation dominated by grasses (*Holcus*, *Poa* and *Lollium* sp). In addition to NemaSlug, the efficacy of refuge traps in combination with NemaSlug treatment will be evaluated. The impact of habitat management (in the form of simple mowing) on molluscs and its effect on NemaSlug treatment will also be assessed.

Materials and methods

The trials were carried out in Cornwall, England at two sites; one located on the Roseland Peninsula, the Porsthscatho site (50°11′49″N; 4°58′26″W) and another near Looe (50° 22′5″N; 4°45′43″W) in central Cornwall. Previous management included plastic cover around the base of the vines to control weeds. Mowing between the lanes is employed at both sites, however, high levels of grass growth is allowed throughout the growing season. Weeds were typically controlled by intensive herbicide spraying, while slug and snail pests were occasionally controlled by metaldehyde-based molluscicides.

A 3×2 factorial design was implemented to study the effects and interactions of biological control (no treatment, NemaSlug, NemaSlug with refuge) and habitat management (mowing, no mowing). Treatments were applied to plots containing 8 vines, targeting the soil around the vines, between the vines and the neighbouring lane.

Rows adjacent to treatment plots were left as buffer zones. The plots were roughly 32m^2 with a minimum width of 4–5 m. Only the central four vines were measured when determining treatment effects. With trapping occurring near the vines, plots of this size give reliable estimates of local slug density without being affected by immigration (Glen et al., 1991; Wilson, Glen, George, et al., 1994). The experimental replicate was plot in this study, 10 plots with each combination of treatment (3×2) occurred at both sites (60 plots per site; $n = 20$ per treatment).

Plots were treated with a single standard field dose of NemaSlug (300,000 nematodes/m^2) using watering cans with a rose attachment with wide diameter perforations (1.5 mm diameter) to allow free dispersal of nematodes (Georgis & Gaugler, 1991; Wilson et al., 1995). NemaSlug was applied on Monday 8th April 2019, with the temperatures at both sites between 10° and12°C and 80% humidity. Application was shortly followed by rainfall at both sites. Refuge treatments (500×750 mm) consisted of metaldehyde-baited refuge traps placed in the centre of plots, made of plastic cover and secured in place with ground hooks. Traps were applied at the same time as treatment. Mowing was carried out one week before the start of treatments and occurred again three weeks after Nemaslug application.

In order to track treatment efficacy, beer traps consisting of two small plastic cups half filled with beer (McEwans Export Ale) were dug to soil surface level at the middle of each treatment plot 4 days post application. Molluscs were recovered after 3 nights. This was repeated at week one, three and five post application. Snail spot counts were carried out on aerial vines at 2, 4- and 6-weeks post-application. Slug were identified in the field primarily to genus level (*Arion spp.* and *Deroceras spp.*) although three taxa were identified to species level: Budapest keeled (*Tandonia budapestensis*), smooth jet (*Milax gagates*) and leopard slugs (*Limax maximus*). Slugs were also categorised by weight and the mean weight per plot was calculated for further analysis.

Accurate determination of pest control efficacy requires crop damage assessment, as *P. hermaphrodita* reportedly does not always have significant effect on slug numbers but can reduce pest feeding (Rae et al., 2009b). The numbers of emerged and total buds were counted to provide a ratio of emerged buds on the central four vines of each treatment plot. This ratio is used as a proxy for plant progress in the early spring. The two longest shoots from either side of the vines were measured and averaged to provide an additional measurement of plant fitness. The number of leaves separated from the longest shoot was also counted. Measurements of plant damage and plant progress were taken at weeks 2, 4 and 6 post-application.

Statistical analysis was carried out in R (R Core Team, 2019). Mixed effects models from the package *lme4* (Bates et al., 2015) were used to analyse the relationships between treatments and various dependent variables. Pseudoreplication was managed through nested random effects in the mixed effects model. The random effects structure was listed as follows: Lane/Plot/(Trap or Vine as applicable). As there were several vines measured and beer traps in each plot, these were included in the first level of the nested random variable. Including plot as a random effect allowed us to account for variation caused by height and exposure, with the vineyards being positioned on steep slopes. Due to the number of plots along each lane, with several plots of each treatment type being present along most lanes, the plot variable was nested in lane. Week of data collection and site were analysed as fixed effects. *P*-values were calculated from likelihood ratio tests after re-fitting maximum likelihood models.

Results

Mowing proved to be an effective means of reducing slug abundance (square root scale; $b \pm SE = -1.061 \pm 0.124$; Likelihood ratio test $\chi^2 = 67.7$, $df = 2$, $P < 0.001$). Biological control treatments did not have a significant effect on slug abundance ($\chi^2 = 0.30$, $df = 2$, $P = 0.86$; Figure 1). The size of slugs was not affected by either biological control treatment ($\chi^2 = 0.227$, $df = 2$, $P = 0.89$) or mowing ($\chi^2 = 2.8$, $df = 2$, $P = 0.094$). However, slugs were found to be significantly larger on the Looe site ($\chi^2 = 21.8$, df = 1, $P < 0.001$). Inspection of data suggested that site and week might have important consequences for efficacy of biocontrol but there was no statistical support for this interaction (site*week*biocontrol treatment, F = 0.86, $df = 4$, $P = 0.49$).

Total snail abundance on aerial vines over the course of the study was reduced by both mowing (0.14 ± 0.061; $\chi^2 = 5.2$, $df = 1$, $P = 0.022$) and biocontrol ($\chi^2 = 48.5$, $df = 1$, $P < 0.001$; Figure 2; square root transformed effect sizes: -4.2 ± 0.075 and -5.3 ± 0.075, respectively).

Habitat management via mowing also reduced the number of damaged buds (square root scale; -0.29 ± 0.028; $\chi^2 = 76.4$, $P < 0.001$). NemaSlug treatment alone was not effective at reducing bud damage, however NemaSlug in combination with refuge traps did reduce the number of damaged buds, although this had a modest effect size (square root scale; -0.08 ± 0.03; $\chi^2 = 7.8$, $df = 2$, $P = 0.02$; Figure 3).

Mowing had a marginally positive effect on bud ratio (square root scale; 0.014 ± 0.006; $\chi^2 = 5.6$, $df = 1$, $P = 0.018$), while biological control did not have a significant effect on bud

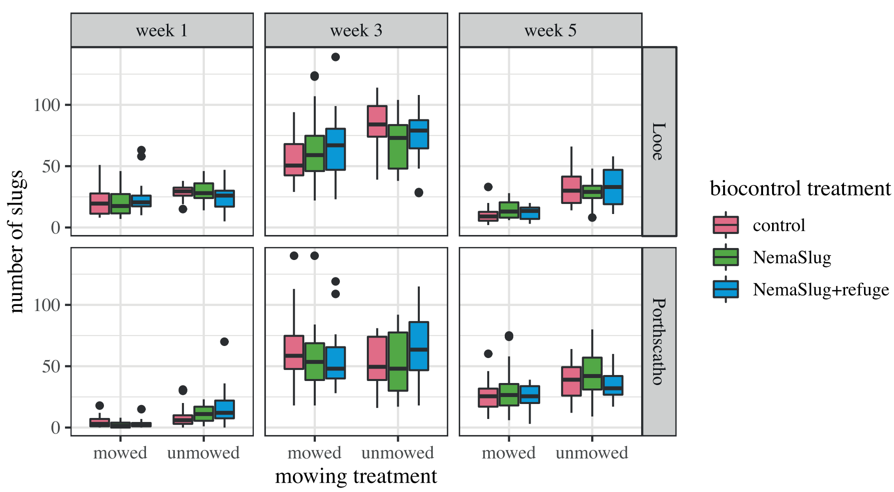

Figure 1. Effects of biocontrol treatment and mowing on slug numbers recovered from beer traps. Panel headings 1–3 indicate the week of sampling, each row corresponds to the two sites in the study. Boxplots show median, first and third quartiles, 1.5 * IQR from the hinge (where IQR is the inter-quartile range). Data beyond the end of the whiskers are outliers.

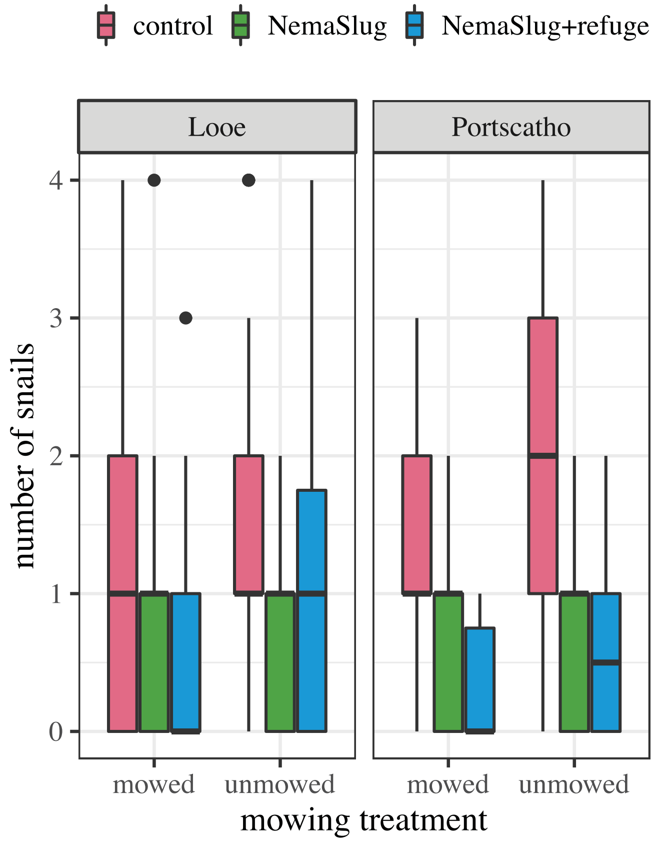

Figure 2. Effects of biocontrol treatment and mowing on snail numbers recovered from aerial vines at two sites. Boxplots showing median, first and third quartiles, whiskers are 1.5 * IQR. Data beyond the end of the whiskers are outliers.

ratio ($\chi^2 = 1.7$, $P = 0.42$, Figure 3). Mowing was found to be marginally effective at supporting plant progression resulting in an increased number of separated leaves (0.14 ± 0.06; $\chi^2 = 4.98$, $df = 1$, $P = 0.026$). Biological control did not have a significant effect on the number of separated leaves ($\chi^2 = 0.31$, $df = 1$, $P = 0.86$). None of the treatments had a significant effect on average shoot length.

Species composition differed between the two sites ($\chi^2 = 1686.3$, $df = 3$, $P < 0.001$). Species belonging to the genera *Arion* and *Deroceras* were dominant on both sites, with *Tandonia budapestensis* only found at the Looe site. Biological control had a small but significant effect on species composition at the Looe site ($\chi^2 = 21.134$, $df = 6$, $P = 0.00173$). NemaSlug and NemaSlug + refuge treated plots had fewer numbers of slugs belonging to susceptible genus *Deroceras* at Looe, while the number of *Arion* slugs was found to be relatively higher on treated plots. Biocontrol did not result in a change in species composition at the Porthscatho site ($\chi^2 = 4.2594$, $df = 4$, $P = 0.372$). Mowing had a significant impact on species composition both at Looe ($\chi^2 = 46.717$, $df = 3$, $p < 0.001$) and Porthscatho ($\chi^2 = 17.036$, $df = 2$, $P < 0.001$) with the largest reduction in numbers seen in the *Arion spp.* (Figure 4).

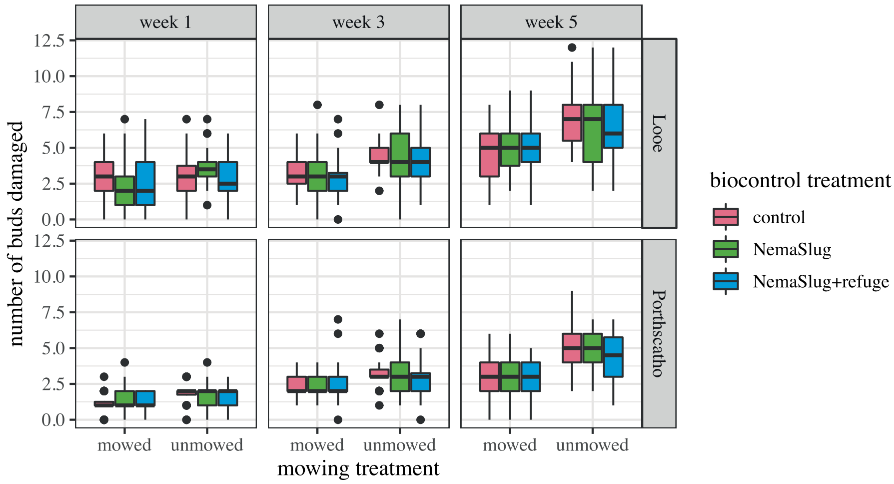

Figure 3. Effects of biocontrol treatment and mowing on the number of damaged buds. Panel headings 1–3 indicate the week of sampling and row indicate study site. Boxplots showing median, first and third quartiles, whiskers are 1.5 * IQR. Data beyond the end of the whiskers are outliers.

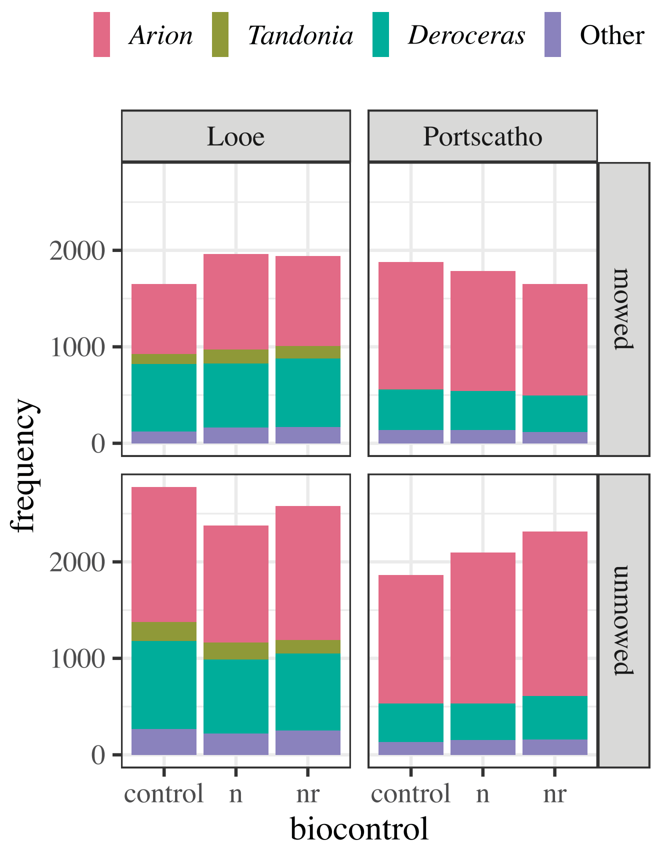

Figure 4. Frequency of slugs found on each site by genus. n = NemaSlug, nr = NemaSlug + molluscicide baited refuge.

Discussion

P. hermaphrodita has been shown to be effective at reducing slug damage in a wide range of crops (Rae et al., 2009b; Wilson et al., 1995; Wilson et al., 2012; Wilson, Glen, George, et al., 1994). We report on the novel application of the biological control product NemaSlug based on the nematode *P. hermaphrodita* on English vineyards. NemaSlug and the combination of NemaSlug and molluscicide-baited refuge traps were found to be ineffective at reducing slug abundance on both experimental sites. The numbers of snails found on aerial vines were significantly lower on both NemaSlug and NemaSlug plus refuge treated plots. This corresponds with previous findings that NemaSlug is capable of parasitising snail pests, although it is not recommended as effective means of controlling these pests (Wilson et al., 2000). Studies on the susceptibility of snails to *P. hermaphrodita* have seen conflicting results. Some studies with *Cepaea hortensis* show susceptibility (Wilson et al., 2000) and others not (Rae et al., 2009a), while feeding inhibition was observed in *C. hortensis* suggesting infection with *P. hermaphrodita* is possible (Glen, Wilson, et al., 2000; Rae et al., 2009a). Snails are not known to show avoidance behaviour for *P. hermaphrodita* (Wynne et al., 2016) although this is known in susceptible slugs and can contribute to lower densities in treated areas. One reason why this study may have found a modest protective effect against snails is that Nemaslug was applied to vegetation, rather than bare soil, so that snails may have been more likely to encounter or ingest nematodes.

Rae et al. (2009b) showed that NemaSlug can reduce the feeding rate of molluscs without necessarily reducing the pest population size. However, we did not find a significant reduction in the number of damaged buds on plots with a straight-forward inundative NemaSlug treatment. In contrast, the combination of NemaSlug and molluscicide-baited refuge traps did have a small effect in reducing bud damage. Slugs have been shown to avoid soils treated by *P. hermaphrodita* (Wilson et al., 1999; Wynne et al., 2016). However, we observed no consistent difference in slug numbers between control plots and NemaSlug treated plots although there were trends in this direction in some weeks. Overall, this suggests that the addition of a molluscicide-baited refuge trap increases the reliability of the Nemaslug treatment.

Slug size can be an important determinant of the success of NemaSlug application. Larger slugs, for example of *Arion spp.* are less affected by the parasitic nematodes, compared to juvenile stages (Speiser et al., 2001). This may contribute to the weak effect of Nemaslug in this trial, since the susceptible *Deroceras* spp slugs made up around a third to a quarter of the slugs at our sites. Nevertheless, we found a lack of variation in slug size between control and treated plots, there was some evidence that Nemaslug affected species composition at one site (Looe) by slightly reducing the proportion of *Deroceras* in the mollusc community. Finally, neither NemaSlug nor NemaSlug in combination with refuge traps had a significant effect on plant progression, potentially because overall densities of molluscs were not at outbreak levels and plants were able to recover. Notably, in previous years very high mollusc densities have been seen to cause substantial, lasting damage at these sites, observations that prompted this study.

There are two potentially contributing factors that may have limited efficacy of NemaSlug in this trial. First, immigration from untreated areas can be an issue in field trials, since slugs can be mobile within crops (Bailey, 1989; Hommay et al., 1998). Field trials with 'mini-plots' of 1–2 m^2 require the use of barriers (Wilson, Glen, Wiltshire, et al., 1994). Nevertheless, field experiments targeting *Deroceras* and *Arion spp.* have shown that large field plots of >30 m^2 are robust to immigration provided samples are taken 2 m from the edge of plots, as we did here (Glen et al., 1991). Field trials on large plots without barriers have repeatedly shown efficacy (Ester, Huiting, et al., 2003; Ester, Van Rozen, et al., 2003; Wilson, Glen, George, et al., 1994), while scaling up field trials from *ca.* 40m^2 to 400m^2 does not obviously affect efficacy (Ester, Huiting, et al., 2003). However, one factor in which this trial differs from previous applications of *P. hermaphrodita* is that applications were not made onto bare soil, as is typical (Ester, Huiting, et al., 2003; Ester, Van Rozen, et al., 2003; Rae et al., 2007; Wilson, Glen, George, et al., 1994). Applications to plants may reduce survival, as seen for entomopathogenic nematodes (Begley, 1990) and may also reduce the contact between surface mobile slugs and nematodes persisting in the soil, although control efficacy of Nemaslug did not change with vegetation cover in a previous trial alternating different cover crops and Chinese cabbage (Vernavá et al., 2004).

Cultural control in the form of simple mowing was found to be effective in reducing slug populations and also helped reduce snail populations on aerial vines. Limited vegetation cover leads to lower abundance of pest species and can allow predators to spot and catch slugs when they breach the soil surface (Allen, 2004; Le Gall & Tooker, 2017; South, 1992), as well as reducing humidity and the availability of food plants. Reduced pest populations are expected to lead to reduced plant damage. We found that mowing was effective at reducing the number of damaged buds, and had a small but positive effect on plant progression measured as bud ratio and the number of separated leaves. Importantly, management of vineyard vegetation differs greatly between vineyards and climates, but is very variable in the nascent cool climate industry. Some cool climate vineyard managers graze sheep between vines partly as a technique for controlling weeds and this might be expected to have a similar effect on mollusc abundance. In warmer climates many growers keep bare soil between the lanes, since competition for water can affect vine health, and water security limits the possibility for cover crops (Garcia et al., 2018). While this would reduce mollusc abundance and activity, concerns over the methods (tilling and herbicide usage) and their effect on soil organic matter (Kazakou et al., 2016) and the reduction of natural enemies of pests (Sharley et al., 2008) can encourage growers towards allowing grass growth between vines (Garcia et al., 2018).

Vineyards provide a great opportunity for the use of novel biological control strategies and development of integrated pest management systems to reduce chemical control measures that are harmful for the environment. Recent restrictions on the use of synthetic molluscicides could leave viticulture in cool and wet climates facing significant terrestrial mollusc damage if effective alternatives to control slug and snail pests are not developed. This study highlights the importance of habitat management and cultural control in sustainable pest management. Vinegrowers have to find the right balance when introducing cultural control accounting for climate conditions, competition for soil resources, composition and abundance of pests.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Availability of data and code

Raw data and code used in statistical analysis are available at the University of Exeter institutional repository ORE at https://doi.org/10.24378/exe.3083.

Author contributions

Material preparation and data collection was performed by AM and ME, and analysis were performed by BR, ZE, and AM. The first draft of the manuscript was written by ZE and ME; all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. All authors contributed to the study conception and design.

ORCID

Zoltan Erdos http://orcid.org/0000-0003-3349-146X
Ben Raymond http://orcid.org/0000-0002-3730-0985
Andrew C. Matthews http://orcid.org/0000-0003-0271-9636

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