Monitoring the EU protected *Geomalacus maculosus* (Kerry Slug): what are the factors affecting catch returns in open and forested habitats?

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Abstract

Geomalacus maculosus is a slug species protected under EU law with a distribution limited to the west of Ireland and north-west Iberia. The species, originally thought to be limited within Ireland to deciduous woodland and peatland, has been found in a number of commercial conifer plantations since 2010. While forest managers are now required to incorporate the protection of the species where it is present, no clear species monitoring protocols are currently available. This study examines the efficacy of De Sangosse refuge traps across three habitats frequently found associated with commercial forest plantations in Ireland and compares them with hand searching, a commonly used method for slug monitoring. Catch data during different seasons and under different weather conditions are also presented. Results indicate that autumn is the optimal time for sampling *G. maculosus* but avoiding extremes of hot or cold weather. While refuge traps placed at 1.5m on trees in mature conifer plantations and directly on exposed rock in blanket peatlands result in significantly greater catches, hand searching is the most successful approach for clear-fell areas. Hand searches in clear-fell preceded by rain are likely to result in greater numbers caught. The results of this study form, for the first time, the basis for *G. maculosus* monitoring guidelines for forestry managers

Keywords: Refuge traps, hand searching, sampling methods, Gastropods, protected species, monitoring

Introduction

The phylum Mollusca, with 85,000 (approx.) described species across aquatic and terrestrial habitats (Chapman, 2009), is one of the most successful animal groups ranked after arthropods and vertebrates (South, 1992). Nevertheless, 42% of all animal extinctions since the 1500s have been molluscan species (Lydeard, 2004). The number of molluscan extinctions alone in the last 400 years outweighs that of birds, mammals, reptiles and amphibians put together (Bouchet *et al.,* 1999). Within Ireland, 150 species of native non-marine molluscs have been evaluated for conservation status and *Geomalacus maculosus* Allman is one of six legally protected mollusc species under European legislation (Byrne *et al.,* 2009). Given the restricted distribution of the species to the west of Ireland and north-west Iberia, *G. maculosus* is protected under Appendix II of the Berne Convention, as well as Annex II and IV of the European Union Habitats Directive (92/43/EC). Irish populations are considered to be of international importance as the Iberian range of the species has been reported as severely threatened and declining (Platts & Speight, 1988; Byrne *et al.*, 2009) and *G. maculosus* is currently listed as vulnerable in Spain (Verdú & Galante, 2006).

Platts and Speight (1988) described *G. maculosus* in Ireland as a "handsome" crepuscular slug, coloured either brown with yellow spots, or grey/black with white spots. Brown specimens are commonly found in woodlands and grey/black specimens in the more open habitats such as blanket bog and heath (Rowson *et al.*, 2014), although some crossover has been found to occur (Platts & Speight, 1988). Originally discovered in Co. Kerry in the south-west of Ireland by Allman in 1842, the species was subsequently found in 1873 and in Portugal and in 1886 in Spain and (Platts & Speight, 1988) with recent research by Reich *et al.,* (2015) indicating that Irish populations are genetically close to those in northern Spain. Given that the species is not found in countries such as France and Britain which lie between north-west Iberia and Ireland (i.e. it has a disjunct distribution), *G. maculosus* is referred to as a Lusitanian species, Lusitania being originally a Roman province corresponding to Portugal and parts of Spain today. In Ireland, *G. maculosus* was traditionally considered to be restricted to the southwest of the country, and within this distribution only in areas of deciduous woodland, blanket bog, unimproved oligotrophic open moor and on lake shores (Anon, 2010). In 2010, however, it was found breeding in a commercial conifer plantation in Co. Galway (Kearney, 2010) 200km (approx.) north of its previously known distribution. Since then, *G. maculosus* has also been discovered in numerous conifer plantations in the south-west of Ireland (Mc Donnell *et al*., 2011; Reich *et al*., 2012).

The Republic of Ireland is one of the least forested countries in Europe, with just over 10% of the land under forest in 2012 of which 68% consists of commercial forestry (Department of Agriculture Food and Marine (DAFM, 2015). Over half of the national forest estate is owned by the state and of this 93% is owned by the state sponsored company Coillte (NFI, 2012). *Picea stichensis* (Bong.) Carr. is the predominant tree planted in commercial plantations in Ireland (DAFM, 2015) and the Forest Service aims to increase forest cover in Ireland to 17% by 2030, primarily through increases in commercial forestry cover (Forest Service 2008). Forestry management is now considered one of the main threats to *G. maculosus* along with invasive species, agricultural reclamation and habitat fragmentation (NPWS, 2013). Prior to 2011, the recommended method for surveying the species was through hand searching (National Roads Authority, 2009). No effective or repeatable trapping method for *G. maculosus* existed until Mc Donnell and Gormally (2011) trialled a range of refuge traps and established that De Sangosse refuge traps were the most effective for surveying *G. maculosus*. De Sangosse traps (0.25m x 0.25m) consist of a layer of absorbent material sandwiched between an upper reflective surface and a black plastic, perforated lower surface. In addition, while Reich *et al.* (2012) used these traps to determine the influence of environmental factors (e.g. temperature) on *G. maculosus* and successfully captured the species for the first time on tree stumps in a forest clear-fell, their data were sourced from a single commercial plantation only.

The presence of *G. maculosus* in commercial conifer plantations in Ireland means that forestry managers are legally obliged to protect the species while undertaking day-to-day forestry practices (e.g. clear-felling). In addition, managers seeking Forest Stewardship Council (FSC) certification (Principle 6) (2016) are required to conserve biodiversity. This requires the development of standardised monitoring protocols so that managers can determine: a) whether *G. maculosus* is present on site; and b) if present, incorporate appropriate management strategies to ensure its protection. However, standardised protocols are not currently available since the optimal positioning of De Sangosse refuge traps in forests and associated habitats such as clear-fell and unplanted areas has not yet been determined. In addition, no comparison to date has been undertaken to compare the effectiveness of using refuge traps with simple hand searching, another commonly used sampling method for *G. maculosus* (NRA, 2009) and other terrestrial gastropods (Hunter 1968). This provided the incentive for this study which for the first time, examines different trapping methods across a range of open and forested sites.

Aims

1. Assess the impact of De Sangosse refuge trap position in forested and open habitats on *G. maculosus* catches and compare these with hand searching.
2. Quantify the effects of seasonal variation on catches to determine the optimum sampling season for site assessment.
3. Determine the influence of temperature and rainfall in forested and open habitats on catches to inform optimum weather conditions during which to undertake sampling.

Materials and Methods

Study areas

Two studies, one carried out over twelve months (Long-term study) and one over four months (Short-term study) were undertaken in and near commercial conifer plantations within the range of *G. maculosus* in the south-west of Ireland. Four study sites (Fig. 1) were chosen within which were selected:

1. Compartments (forestry management unit) of mature commercial conifers (predominantly *P. stichensis*) planted on peatland in the early 1970s (Coillte, 2015).
2. A compartment, which was clear-felled in 2013 and, at the time of the study, was dominated by *P. sitchensis* tree stumps interspersed with *Digitalis purpurea* L., *Juncus effusus* L. and mosses.
3. An adjacent area of unplanted peatland containing predominantly *Molinia caerulea* (L.) Moench, and *Calluna vulgaris* (L.) Hull.

While another slug species (*Lehmania marginata* Müller) was also found in conifer plantations during the study, catches were, on average, 96% lower than those for *G. maculosus*, the focal species for this investigation.

Long-term Study

The aim of the long-term study was to record catches of *G. maculosus* from a range of habitats over a full calendar year with a view to determining the optimum season for sampling using refuge traps (De Sangosse, Pont du Casse, France, hereafter referred to as "trap"). In each mature compartment, a stand of nine trees in a 3 x 3 grid was selected, at least 10m from the edge of the forest. As in Mc Donnell & Gormally (2011), a single trap was fixed to the north side of each tree (using nails and string) at 1.5m above ground (Fig. 2a). Similarly, in each of the clear-fell compartments, individual traps (secured using nails and string) were placed on the north side and top of 3 x 3 tree stumps (Fig. 2b) situated at least 10m from the compartment edge. At each of the peatland sites, nine traps were placed on rocks as per Mc Donnell & Gormally (2011) using tec7 glue, nails and string (Fig 2c). In addition, in each mature conifer and clear-fell compartment and in the peatland sections (at a minimum distance of 45m from the tree, stump or rock traps respectively), nine (3 x 3) traps (1.5m apart) were secured (using tent pegs) over vegetation/bare soil on the ground between the traps on trees, tree stumps and rocks. These traps (hereafter referred to as "ground traps") were deployed because McDonnell & Gormally (2011) have shown that *G. maculosus* can move between trees.

Slug catches under the traps were recorded each day for five consecutive days every month for 12 months from September 2014 to August 2015 and because of this, traps were not baited as in Mc Donnell & Gormally (2011) since bait degradation would occur between sampling months, thereby influencing the catches on day 1 of each monthly sampling period. The age (i.e. adult or juvenile) and location (i.e. on tree, stump, rock, or ground) of every *G. maculosus* found under the traps were recorded. As the size of *G. maculosus* is difficult to measure, and weighing individuals was problematic in the field, slugs greater than 1cm in diameter when rolled into a defensive ball were deemed to be adults.

Short-term study

During the final four months of the long-term study, an additional investigation was undertaken to compare the sampling protocols of Mc Donnell and Gormally (2011) with previously untried sampling methods. This study was completed at additional locations within each of the four field sites above but using the same protocol regarding distances between traps. The aims were to compare:

a) Efficacy of traps placed on mature trees at 1.5m versus 0.2m above ground

For this study, two additional mature stands of nine trees (3 x 3) were selected within each of the mature compartments included in the long-term study. Traps were placed on the north side of the trees at a standard height of 1.5m (stand 1) and at a height of 0.2m from the base of the tree (stand 2). To avoid any potential bias related to individual trees, traps placed at 0.2m were relocated to 1.5m on the same tree and vice-versa at the end of each sampling week. Sampling regime followed that of the long-term study.

b) Efficacy of traps versus hand searching

Hand searches were also undertaken in the mature and clear-felled compartments, and in the adjacent peatland at a distance of 45m from all other trapping locations. Hand searches were completed on nine trees (3 x 3) in the mature compartment, nine stumps (3 x 3) in the clear-fell compartment and over a marked area of similar size (5m x 5m), respectively on the peatland outcrops. Hand searches for both adult and juvenile *G. maculosus* were carried out by two people for five minutes per person in each of the designated areas giving a total of ten minutes searching for each sampling day between June and September 2015. This is equivalent to the minimum amount of time it took to check traps for catches within the compartments. Searches involved examining primarily lichens and mosses on tree trunks (to a maximum height of approximately 2m), stumps and rocks in addition to examining the areas in between these features.

Temperature and rainfall data collection

TinyTag Plus 2 (TGP-4500) environmental data loggers were used to collect temperature data with readings taken every 20 minutes from 19th of September 2014 to the 31st of August 2015. Each data logger, placed 1m above ground in a Stephenson's Type Screen (ACS-5050, TinyTag), was placed in each mature conifer and clear-fell compartment and in the peatland sections between the groups of traps. The Screen protects TinyTag loggers from direct sunlight and precipitation when monitoring outdoors (TinyTag, 2016). Hourly rainfall data were obtained from the nearest Met Éireann (Irish National Meteorological Service) stations in Cork Airport, Co. Cork, and Valentia, Co. Kerry to allow for an assessment of the influence of rainfall on capture success. These weather stations were selected as Site 1 was nearest (31 km) to Valencia and Sites 2 (53km), 3 (48km), and 4 (53km) were closest to Cork airport.

Statistical analyses

All analyses were undertaken using SPSS version 21. Where the assumptions of normality and homogeneity of variance were violated, Welch's T test or ANOVA was used followed by a Games-Howell *post hoc* test to determine pair-wise differences where more than two groups were examined. Where the assumption of normality was violated but the homogeneity of variance was not, the Kruskal Wallis H test was used followed by a Dunn's *post hoc* test to compare pair-wise differences. Curve estimation was also used to assess the relationship of examined variables to each other. Where linear relationships were found two-tailed Spearman rank correlations were performed. Mean temperature over seasons was calculated by averaging readings taken every twenty minutes from data loggers over the course of the investigation.

Results

Comparison of trap position and hand searching on *G. maculosus* catches in forested /open habitats (Short-term Study)

Six hundred and fifty-six adult and 63 juvenile (8.8% of total catch) *G. maculosus* were caught on 135 sampling occasions in the mature forest compartments with all individuals caught by hand searching found on tree trunks only (Table 1). Adult / juvenile catches were greatest using traps placed on tree trunks 1.5m above ground (412 / 39), followed by traps placed at 0.2m above ground (219 / 21), hand searching (20 / 3) and traps placed directly on the ground (5 / 0). For adults statistically significant differences were found between all sampling methods (P < 0.001, Welch's ANOVA followed by Games-Howell *post-hoc* analysis) except between traps placed directly on the ground and hand searches. For juveniles statistically significant differences were found only between traps placed at 1.5m and hand searching (P = 0.020, Welch's ANOVA with Games-Howell *post-hoc* analysis). No juveniles were found beneath ground traps. Where juveniles were caught the percentage of the overall catch consisting of juveniles for individual sampling methods was greatest for hand searching (13% of total catch) compared to traps at 1.5m (8.6% of total catch) or 0.2m above ground (9.5% of total catch).

One hundred and forty-four adult and 29 juvenile (16.8% of total catch) *G. maculosus* were caught over 80 sampling occasions in the clear-felled compartments (Table 2). Adult / juvenile catches were greatest using hand searching (99 / 27), followed by traps placed on stumps (36 / 2), and traps placed directly on the ground (9 /0). For adults statistically significant differences were found between all three methods (P < 0.001, Welch's ANOVA with Games-Howell *post-hoc* analysis). For juveniles, statistically significant differences were found between hand searches and traps placed on tree stumps (P = 0.037, Welch's T-test with Games-Howell *post-hoc* analysis). No juveniles were found beneath ground traps and all adults and juveniles (126 in total) caught by hand searching were found on tree stumps only. Where juveniles were caught the percentage of the overall catch consisting of juveniles for individual sampling methods was greatest for hand searching (21.4% of total catch) compared to tree stump traps (5.3% of total catch).

Forty-four adult and 17 juvenile (27.9% of total catch) *G. maculosus* were caught over 80 sampling occasions on the rock outcrops on the peatland (Table 3). Adult and juvenile catches were greatest using rock traps (42 / 14), followed by hand searching (2 / 3), and none were captured under traps placed directly on the vegetation between the rocks (ground traps). Statistically significant differences were found between rock traps and hand searching for both adults and juveniles ($P = 0.029$, Welch's T-test). All adults and juveniles (5 individuals) caught by hand searching were found on rocks only. Where juveniles were caught the percentage of the overall catch consisting of juveniles for individual sampling methods was greatest by hand searching (60% of total catch) compared to rock traps (25% of total catch).

Seasonal variation in *G. maculosus* catches (Long-term study)

Catches are reported as mean number of *G. maculosus* caught per sampling occasion to allow for comparison across the seasons (Table 4). Mean number of adults caught using traps was greatest in the autumn (4.62), followed by spring (2.43) and summer (1.62), with lowest catches occurring in the winter (1.43). Mean number of juvenile caught was also greatest in autumn (0.38), followed by summer (0.36), spring (0.14) and winter (0.12). Autumn catches for both adults and juveniles were significantly greater ($P = 0.000$; $P = 0.001$ respectively) than winter and spring catches ($P < 0.001$; $P = 0.002$ respectively), Welch's ANOVA with Games-Howell post-hoc analysis. Additional significant differences in adult and juvenile catches between seasons can be seen in Table 4. The percentage of the total catch represented by juveniles was greatest in the summer (18.3%) followed by winter (7.9%), autumn (7.7%) and spring (5.4%).

In the mature conifer compartments lowest mean catch in winter corresponded with the lowest average temperatures and second lowest catch success in summer corresponded with the highest mean temperatures (Fig. 3). In both the clear-fell compartments and peatland sections the lower catches generally occurred in winter and spring (peatland) and winter, spring and summer (clear-fell) (Fig. 3).

G. maculosus catches in relation to temperature and rainfall (Long and short term studies)

Significant, but weak, quadratic relationships (Fig. 4) were found between total capture success using refuge traps placed at 1.5m and average temperature during the 24 hour period prior to sampling in mature conifer compartments (P < 0.001, r_s = 0.069) and in clear-felled compartments (P < 0.001, r_s = 0.053) (Fig. 4). There was no significant relationship between temperature and capture success in peatland areas (P = 0.167, r_s = 0.020). Significant, but weak, quadratic relationships were also found between capture success and average temperature over the twenty minutes it took to assess traps in mature conifer compartments (P < 0.001, r_s = 0.067) and in clear-felled compartments (P = 0.024, r_s = 0.029) (Fig. 4). There was no significant relationship between temperature and capture success in peatland areas (P = 0.072, r_s = 0.024).

Significant, but weak, negative Spearman's rank-order correlations were found between individuals caught using hand searches and both the average temperature during the 24 hour period prior to sampling and the temperature during hand searching (P = 0.038, r_s= -0.268, and P = 0.012, r_s= -0.279 respectively) in clear fell compartments. No significant correlations were found between hand search catch success and average temperature during the 24 hour period prior to sampling in either mature conifer compartments (P = 0.689, r_s = 0.040) or peatland sections (P = 0.651, r_s=0.060). Furthermore, no significant correlations were found between hand search catch success and temperature during hand searching in either mature conifer compartments (P = 0.689, r_s= 0.040) or peatland sections (P = 0.651, r_s= 0.060).

A significant, moderate positive Spearman's rank-order correlation was found between individuals caught using hand searches and the average rainfall during the 24 hour period prior to sampling (P = 0.001, r_s = 0.371) in clear-fell compartments. No significant correlations were found between hand search catch success and average rainfall during the 24 hour period prior to sampling in either mature conifer compartments (P = 0.368, r_s = -0.078) or peatland sections (P = 0.226, r_s = 0.137). Additionally, no significant correlations were found between hand search catch success and rainfall during hand searching in either mature conifer compartments (P = 0.242, r_s = -0.101), clear-fell compartments (P = 0.487, r_s= 0.079), or peatland sections (P = 0.334, r_s= -0.109).

Discussion

Trap position / hand searching and *G. maculosus* catches

Within the mature forest compartments, traps placed at a standard height of 1.5m had greater catch success for adults and juveniles combined (63% of total catch) compared to traps placed at 0.2m (33%), hand searching (3%) and ground traps (< 1%). While Platts & Speight (1988) list the forest floor in deciduous forests as a potential microhabitat for *G. maculosus*, a small study by Mc Donnell & Gormally (2011) in a native oak-birch-holly woodland found more individuals under identical traps placed at 1.5m on tree trunks than under ground traps albeit made of a range of different materials. It is, therefore, likely that individual trees are an important microhabitat for *G. maculosus* with most slug activity in commercial conifer plantations occurring on trees rather than on the ground between trees. The fact that ground traps in mature plantations resulted in the least number of catches and no slugs were caught on the forest floor during hand searches further strengthens this conclusion. While lichens, the primary food plant of *G. maculosus* (Reich *et al.,* 2012), are more species rich in the upper third of trees in Sitka spruce plantations (Coote *et al.*, 2007), humidity also decreases with increasing elevation on trees (Hosokawa *et al.,* 1964). It is probable that while slugs may forage in the upper parts of the tree, they return to the more humid, shaded conditions found in the lower parts of the trees to avoid desiccation. This being the case, the first trap they would encounter as they move down the tree would be the trap placed at 1.5m where almost twice as many individuals were caught in comparison to catches under traps placed at 0.2m. The likely movement of individuals up and down the tree trunks may have contributed to the relatively poor efficacy of hand searching in the mature conifer compartments simply because, for practical reasons, counts of slugs on tree trunks were limited to a maximum height of 2m.

In clear-felled compartments, hand searching yielded the greatest catches of adults and juveniles combined (73% of total catch) compared to tree stump traps (22%) and ground traps (5%). Allowing for differences in numbers of traps employed and numbers of sampling occasions at the mature forest and clear-felled compartments, catches at the mature forest compartments overall were almost double those at the clear-felled compartments. While this is likely to be a reflection of the actual numbers in each habitat type, another possible reason for the relatively low capture rates using traps, in particular, is that the exposed nature of clear-fell areas often resulted in the area immediately beneath the traps drying out, making them less attractive to slugs wishing to use them as shelters. In comparison, traps deployed on tree trunks in plantations tended to remain damp for longer possibly due to the flow of water down the trunk of trees following rainfall (Ovington, 1954) in conjunction with the more shaded conditions beneath the tree canopy. Given that only 23% of all individuals captured on tree stumps were found beneath traps compared to 77% by hand searching also suggests that traps did not function at an optimal level in this habitat. In addition, the total number of captures using traps in the clear-fell (47) is close to that found beneath traps in the other exposed habitat studied i.e. peatland (56) with exactly the same sampling effort. That no slugs were found between stumps when hand searching could be the result, in some cases, of the presence of *J. effusus* and *D. purpurea* making it difficult to see specimens. Indeed, McDade and Maguire (2005) have noted that when surface conditions are more structurally complex it becomes more difficult to detect slugs using hand searching.

In peatland sections traps placed on rocky outcrops had the greatest catches of adults and juveniles combined (92% of total catch) compared to hand searching (8%), with no individuals found beneath traps placed directly on the ground between rocks. This mirrors the findings by Mc Donnell & Gormally (2011) who successfully captured *G. maculosus* with traps placed on rocky outcrops in peatland. Individuals captured using hand searching were also found only on rocky outcrops within the hand searching area. It is likely that successful capture of slugs was limited to rocks because of the presence of an abundant source of lichens on which *G. maculosus* feeds (NRA, 2009). The absence of individuals found either by hand searching and under traps placed on the ground between rocks indicates the importance of outcrops as a habitat feature for the species in peatland habitats. Having said that, dense vegetation in peatlands, particularly the presence of *M. caerulea*, may reduce the effectiveness of hand searching. In addition, the absence of catches under ground traps placed between rocks in this study may reflect genuinely low abundances in that *G. maculosus* has only been rarely seen on open peatland vegetation (Mc Donnell, *pers.comm*.). It is, however, possible that higher levels of moisture in peatland vegetation may reduce the attractiveness of the traps as a refuge from desiccation unlike those in the drier conifer compartments.

In terms of juvenile capture success, while overall numbers caught were lower than those of the adults, trends observed followed those of the adults in each of the three habitats. Although greatest numbers of juveniles were caught using traps (excepting ground traps) in both mature conifer compartments and peatland, the proportion of juveniles caught in each of the three habitats was consistently greater using hand searching compared to using traps. Rollo and Wellington (1979) found that adults of *Deroceras reticulatum* Müller, four *Arion* species and *Limax maximus* L. tended to be more aggressive than juveniles which resulted in juveniles being unable to compete with the larger adult slugs for shelters. In addition, Rollo (1982) in a later study found that juvenile slugs (*Deroceras* species, *Arion species* and *L. maximus*) spent a larger portion of their active period foraging. It is, therefore, possible that a combination of competition for shelter and more time spent foraging resulted in lower proportions of juveniles found under traps. Where there are time constraints and simply presence or absence data are required, initial hand-searching under appropriate weather conditions and during the appropriate season is probably sufficient. Hand searching at night (using torches) could yield interesting results and the effect on catches of searching at different times of the day is worth further investigation. If no specimens are found by hand-searching, traps could be placed subsequently to confirm the presence or absence of the species. Traps are also useful in instances where personnel undertaking hand-searching are inexperienced and in cases where long term monitoring is required. Weighing of slugs in the field (time permitting) would permit researchers to separate with more precision the different age stages and further our understanding of *G maculosus* population dynamics in the field.

Geomalacus maculosus catches – in relation to temperature and rainfall

While *G. maculosus* was collected year round, results of the long-term study indicate that capture success varies across the seasons. Capture success for both adults and juveniles was greatest during the autumn months and least in winter. After autumn, spring and summer catches were the next highest for adults and juveniles respectively. The results suggest that *G. maculosus* monitoring surveys and / or relocation prior to clear-felling should be undertaken during autumn to ensure optimal catch success. The second peak in juvenile catches in summer is likely to be the result of egg laying by adults in the spring (Wisniewski, 2000). Summer surveys would therefore provide useful information on the health of the population by indicating the extent of breeding and recruitment by juveniles. Further research whereby populations are monitored over a number of years (ideally with different weather patterns) would further refine optimum sampling seasons for the species. Significant but weak quadratic relationships were detected between temperatures during the 24-hour period prior to and at the time of sampling with capture success using traps in both mature conifer and clear-felled compartments. No significant relationship was found in the peatland sections where trap catches were overall substantially less. The quadratic nature of the relationships suggests that both low and high temperatures have a negative effect on numbers of individuals found beneath traps in mature conifer/ clear-felled compartments. It is likely that the oceanic nature of climate in Ireland with its relatively small temperature range (Met Éireann, 2016) may have contributed to the weak relationship between temperatures and slug catches. Nevertheless, catches at each of the three sites were lowest in winter (corresponding to the lowest mean temperatures) and although catches were next lowest in summer (highest mean temperatures) at the mature conifer plantations, this was not the case for the clear-fell and peatland habitats where numbers of catches were substantially lower. It is interesting to note that in clear-fell compartments, where hand searching was most successful, there was a negative correlation between numbers of individuals caught by hand searching and average temperatures prior to and during sampling. Coupled with this was the positive correlation between individuals caught using hand searches in clear-fells and the average rainfall during the 24 hour period prior to sampling. Given that hand searching has been reported as being highly dependent on weather (Bruelheide & Scheidel, 1999), there are clearly a number of factors at play relating to the attractiveness of traps coupled with levels of slug activity under different weather conditions.

As previously mentioned, it is possible that at higher air temperatures the surface beneath the traps dries out, particularly in clear-felled compartments, making them less attractive to *G. maculosus* thereby resulting in lower catches. Terrestrial slugs are known to be extremely susceptible to dehydration (Cameron, 1970), and seek to avoid exposure to unfavourable conditions as a means of protecting themselves (Rollo, 1982). Additionally, slugs in general are known to move down through the soil profile to avoid freezing temperatures (Cook, 2004). In support of this the authors have observed *G. maculosus* sheltering below ground and under the moss cover at the bases of trees, stumps and rocks during warm and dry weather, as well as during cold weather. With regard to rainfall, it is interesting to note that no significant relationship was found between rainfall at the time of sampling and hand search capture success in any of the habitats. This finding is somewhat surprising given that *G. maculosus* is reported to be only diurnally active during or after rain (Taylor 1906; Platts & Speight, 1988). Given that rainfall data were sourced from weather stations more than 30km from the sites, they may not have reflected local variation in rainfall accurately. In addition, Ovington (1954) found that duration and intensity of rainfall are the most important factors dictating the amount of rainfall that reaches the ground in conifer plantations. It has been widely reported that temperature and rainfall are important factors influencing slug activity in general (Barnes & Weill, 1945; Webley *et al.,* 1964; Young, 1991; Shirley *et al.*, 2001; Choi *et al*,. 2006) and this is, to some extent, reflects the results of this study. Although logistics in this study did not permit the recording of weekly catch data, future studies incorporating on-site weather data, particularly rainfall measurements in addition to weekly catch data would further refine the relationship between weather conditions and catch success.

The results of this study clearly indicate for the first time that approaches to monitoring *G. maculosus* needs to take into account the habitat under investigation. Of the sampling strategies investigated in this study, traps placed at a height of 1.5m on trees in mature conifer plantations will likely result in optimal numbers of catches of *G. maculosus*. In clear-fell areas, hand searching under suitable weather conditions, preferably when rain has fallen in the previous twenty-four hours, is recommended. For peatlands, traps should be placed on exposed rock. Overall, autumn is the preferred time of sampling for adult slugs, while summer sampling is recommended if breeding and recruitment studies are required. Sampling during extremes of hot and cold weather should be avoided as results are likely to give an underestimation of slug densities, which could lead to the implementation of poor management decisions. While the results of this study form the basis for guidelines to forestry managers who are legally obliged to protect *G. maculosus* when undertaking routine forestry practices, further work regarding the presence of the species in the upper canopy is required. In addition, measuring humidity and temperature beneath traps using probes in conjunction with numbers of slug catches will further refine how best to maximise the use of trap data for the protection of *G. maculosus* in the future.

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Table 1 Mature Forest: Total and mean (±SD) catch of adult and juvenile *G. maculosus* using traps placed on trees 1.5m above ground, 0.2m above ground, directly on the ground and using ten minute hand searches from June to September 2015 (N = 135 sampling occasions).

	1.5m traps	**0.2m traps**	**Ground traps**	**Hand search**
Adult				
Total catch	412	219	5	20
Mean ± SD	3.05 ± 5.00	1.62 ± 3.41	0.05 ± 0.23	0.15 ± 0.38
1.5m trap	-	-	-	-
0.2m trap	**0.033**	-	-	-
Ground traps	**0.000**	**0.000**	-	-
Hand search	**0.000**	**0.000**	0.080	-
Juvenile				
Total catch	39	21	0	3
Mean ± SD	0.34 ± 1.24	0.16 ± 0.67	0	0.02 ± 0.15
1.5m trap	-	-	-	-
0.2m trap	0.081	-	-	-
Ground trap	**-**	-	-	-
Hand search	**0.020**	0.296	-	-

Adult: Test statistic = 26.635; df = 3; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between trapping methods, Games-Howell multiple comparison test; **Juvenile:** Test statistic = 4.696; df = 2; $P = 0.010$, Welch's ANOVA. *P* values given in bold indicate significant differences between trapping methods, Games-Howell multiple comparison test.

Table 2 Clear-felled compartments: Total and mean **(**±SD) catch of adult and juvenile *G. maculosus* using traps placed on tree stumps, on the ground and using ten minute hand searches from June to September 2015 (N=80 sampling occasions)

	Tree stump traps	**Ground traps**	**Hand search**
Adult			
Total catch	36	9	99
Mean ± SD	0.45 ± 0.81	0.11 ± 0.36	1.82 ± 2.82
Tree stump traps	-	-	-
Ground traps	**0.003**	-	-
Hand search	**0.011**	**0.000**	-
Juveniles			
Total catch	2	0	27
Mean ± SD	0.03 ± 0.16	0	0.34 ± 1.31
Tree stump traps	-	-	-
Ground traps	-	-	-
Hand search	**0.037**	-	-

Adult: Test statistic = 14.690; df = 2; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between trapping methods, Games-Howell multiple comparison test; **Juvenile:** Test statistic = 4.478; df = 1; $P = 0.037$, Welch's T-test. *P* values given in bold indicate significant differences between trapping methods, Games-Howell multiple comparison test.

Table 3 Peatland: Total and mean (±SD) catch of adult and juvenile *G. maculosus* using refuge traps placed on rocks (rock traps, on vegetation among rocks (ground traps) and using ten minute hand searches from June to September 2015 (N = 80 sampling occasions)

	Rock traps	**Ground traps**	**Hand search**
Adult			
Total catch	42	0	2
Mean ± SD	0.53 ± 0.84	0 ± 0	0.03 ± 0.16
Rock traps	-	-	-
Ground traps	-	-	-
Hand search	**0.000**	-	-
Juveniles			
Total catch	14	0	3
Mean ± SD	0.18 ± 0.50	0 ± 0	0.38 ± 0.25
Rock traps	-	-	-
Ground traps	-	-	-
Hand search	**0.029**	-	-

Adults: Test statistic = 27.288; df = 1 $P < 0.001$ Welch's T test. *P* values given in bold indicate significant differences between trapping methods; **Juveniles:** Test statistic = 4.890; df = 1 $P = 0.029$ Welch's T test. *P* values given in bold indicate significant differences between trapping methods.

Table 4 Seasonal variation: Adult and juvenile *G. maculosus* catches in autumn (N=230), winter (N=245), spring (N=245), and summer (N= 225) across all three habitats using refuge traps (mature forest, clear-fell and peatland).

	Autumn 14	**Winter 14/15**	**Spring 15**	**Summer 15**
Adult				
Total catch	1062	349	596	358
Mean ± SD	4.62 ± 6.53	1.43 ± 2.70	2.43 ± 3.95	1.64 ± 2.97
Autumn	-	-	-	-
Winter	**0.000**	-	-	-
Spring	**0.000**	**0.006**	-	-
Summer	**0.000**	0.0837	0.068	-
Juvenile				
Total catch	88	30	34	80
Mean ± SD	0.38 ± 0.96	0.12 ± 0.44	0.14 ± 0.42	0.36 ± 0.95
Autumn	-	-	-	-
Winter	**0.001**	-	-	-
Spring	**0.002**	0.975	-	-
Summer	0.997	**0.003**	**0.006**	-

Adults: Test statistic = 17.813; df = 3; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between seasons Games-Howell multiple comparison test. **Juveniles:** Test statistic = 9.280; df = 3; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between seasons Games-Howell multiple comparison test

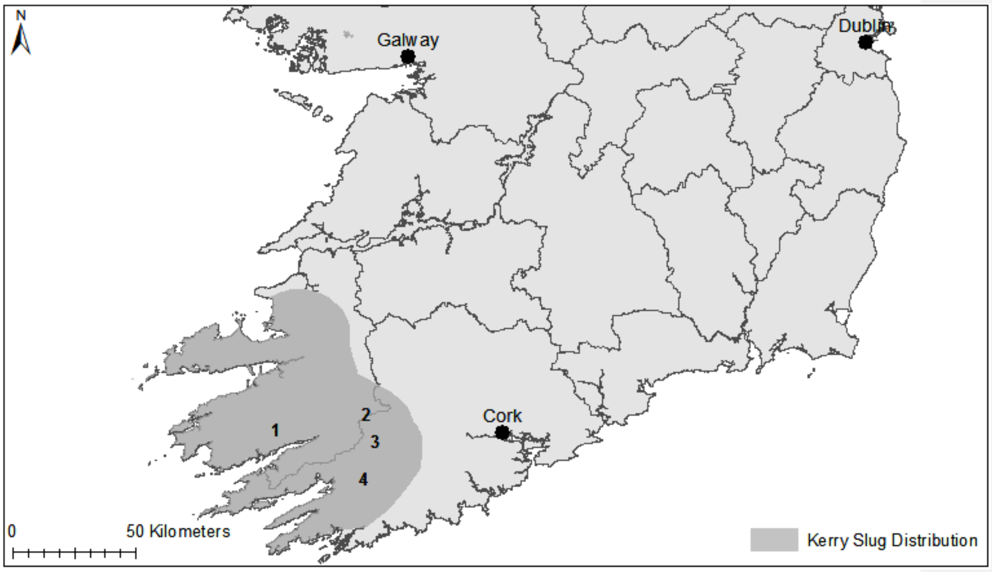

Fig. 1 Location of the four study sites in the south-west of Ireland: Site 1 (Tooreenafersha), Site 2 (Derrynasaggert), Site 3 (Rathgaskig/Coomlibane) and Site 4 (Barnagowlane) (G. Kindermann, 2016)

Fig. 2 Traps placed on a tree (a), a tree stump (b), and a rock (c) (G. Kindermann, 2016)

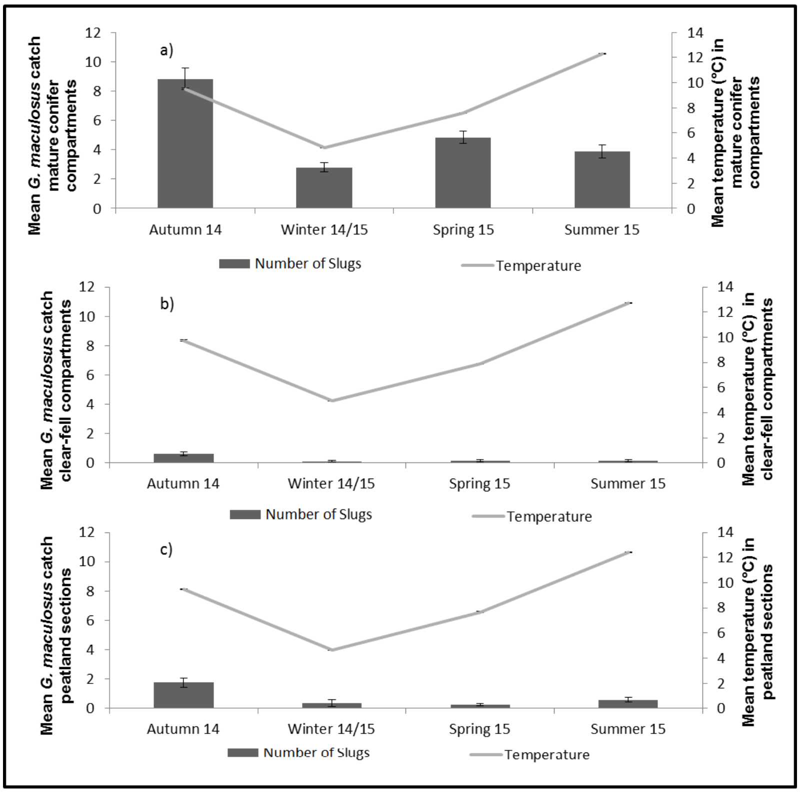

Fig. 3 Mean (±SE) *G. maculosus* individuals (bar graph) caught (using traps) in mature conifer compartments (a), clear-felled compartments (b), and peatland compartments (c) with mean temperature (◦C ± SE) (line graph) for each season, from September 2014 to November 2014 (autumn), December 2014 to February 2015 (winter), March to May 2015 (spring) and June to August 2015 (summer).

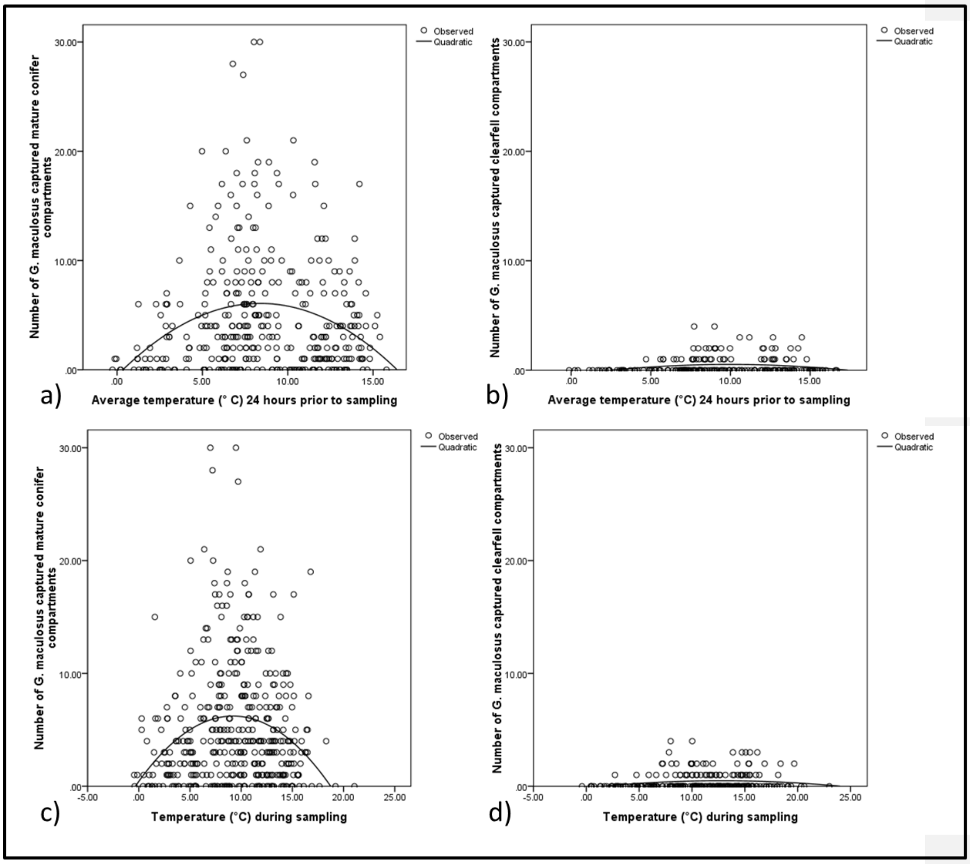

Fig 4 Quadratic relationship (line) between *G. maculosus* individuals caught (using traps) and average temperature (°C) 24 hours prior to sampling in mature conifer compartments (a), and in clear-fell compartments (b). Quadratic relationship (line) between *G. maculosus* individuals caught (using traps) and temperature (°C) during sampling in mature conifer compartments (c), and in clear-fell compartments (d) between October 2014 and August 2015.

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