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ORIGINAL PAPER

Mature exotic conifer stands have greater catches of the EU-protected *Geomalacus maculosus* than adjacent peatland or clear-felled stands—implications for forestry

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Abstract

• ***Key message*** **Mature exotic Sitka spruce (*Picea sitchensis*; Bong. Carrière)-dominated stands, particularly trees of greater circumference, result in greater numbers of *Geomalacus maculosus* (Allman) captures than adjacent clear-felled stands and adjacent peatland with Before-After-Control-Impact-Paired analysis indicating lower catches of *G. maculosus* post-felling.**

• ***Context*** The discovery of EU-protected *Geomalacus maculosus* in commercial plantations requires an understanding of the implications of forestry practices for the species within the context of sustainable forest management.

• ***Aims***

1. Compare *Geomalacus maculosus* captures across mature exotic Sitka spruce-dominated stands, previously clear-felled stands and adjacent peatland habitats.
2. Assess the suitability, for forest managers, of population estimate models for *G. maculosus*.
3. Assess the implications of felling by comparing relative abundances of *G. maculosus* directly before and after clear-felling at a mature exotic Sitka spruce-dominated stand.

• ***Methods*** *Geomalacus maculosus* catches were compared at four sites across two to three mature (43–45 years old) conifer stands per site, one clear-felled stand per site, and one adjacent peatland per site using refuge traps and hand searching. Capture-mark-recapture studies were undertaken to estimate population sizes. A BACIP (Before-After-Control-Impact-Paired) analysis was undertaken in one forest stand at one forest site to determine impacts of a clear-felling event.

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Contribution of the co-authors Erin Johnston undertook the fieldwork, analysed the data and wrote the manuscript. Gesche Kindermann assisted with site selection and fieldwork and edited the manuscript. Jack O'Callaghan, Daniel Burke, Cillian McLoughlin and Sinéad Horgan contributed to data collection and assisted with fieldwork. Inga Reich assisted with population estimates and gave advice on tagging *G. maculosus*. Rory Mc Donnell provided specialist advice, assisted with site selection/experimental design and edited the manuscript. Christopher Williams provided statistical advice and edited the manuscript. Michael Gormally designed and supervised the project and acted as senior editor for the manuscript.

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• ***Results*** Mean catches of *Geomalacus maculosus* adults in the mature forest stands were over 10 and 11 times greater than mean catches on peatland and clear-fell stands, respectively. The Schnabel model for estimating population size was most suited for mature forest stands but could not be utilised for the other habitats. BACIP analysis showed a significant impact of clear-felling with a 95% reduction in mean *G. maculosus* catches after a clear-felling event where none of the individuals marked prior to felling were recaptured compared to 21% recapture rates at the control site. Greater tree circumference in mature conifer stands correlated with greater catches.

• ***Conclusion*** Guidelines are needed to ensure the protection of *Geomalacus maculosus* in commercial forestry. Interventions could include patch/tall stump retention at final felling and/or translocation of the protected species.

Keywords Conservation · Capture-mark-recapture · Population estimates · Before-After-Control-Impact-Paired (BACIP) · Slug

1 Introduction

The Kerry Slug (*Geomalacus maculosus* Allman, 1943) has a disjunct distribution and is referred to as a Lusitanian species in that it is restricted solely to western Ireland and north-western Iberia (Scharff 1893; Patrão et al. 2015). The species is protected under the European Union Habitats Directive (92/43/EC) and the Wildlife (Amendment) Act 2000 in Ireland. As its status is listed as “inadequate” but improving in Spain and there are no current assessments available for Portuguese populations (EIONET 2014), Irish populations of the species are considered to be of international importance. In Ireland, *G. maculosus* was originally considered to be associated with deciduous woodland and peatlands (such as blanket bog and unimproved oligotrophic open moor) in the south-west of the country (Anon 2010) where it is known to take refuge in rock crevices, soil or bark (Platts and Speight 1988). Consequently, these habitats have been the focus of conservation efforts for the species (Anon 2010). However, in recent years, Kearney (2010) discovered the species breeding in a commercial conifer plantation in Oughterard (Co. Galway) 200 km north of its previously known distribution. Since then, it has also been found in numerous conifer plantations in the south-west of Ireland (Mc Donnell and Gormally 2011). Although there is no empirical evidence to date regarding how *G. maculosus* became established in commercial conifer plantations, it is possible that, as planted trees in the south-west of Ireland matured, they were colonised by the slug from surrounding peatlands in which the species was naturally present. It has also been hypothesised by Reich et al. (2012) that the population in Oughterard was introduced by forestry machinery. Although *G. maculosus* is known to eat lichens and mosses on blanket bogs, it also feeds on lichens, mosses and liverworts commonly found growing on the trunks of mature conifers in commercial plantations (Reich et al. 2012). While little is known regarding the use by *G. maculosus* of micro-habitats within the tree canopy, it is likely that the species occurs in the upper reaches of mature conifer trees where lichens also proliferate. *Geomalacus maculosus* is rarely seen or trapped on the ground between trees (Johnston et al. 2017), but it is found beneath mosses at the base of mature conifers in unsuitable weather conditions (i.e. dry or cold) during which time the species is generally absent from the portion of tree trunks visible from ground level (*pers. obs.*).

Some studies indicate that biodiversity can be enhanced by forest plantations, but this is more likely to happen when native tree species are planted and forest plantations do not supplant natural ecosystems (Bremer and Farley 2010; Carnus et al. 2006). In addition, practices such as clear-felling, the norm for harvesting commercial conifer plantation stands in Ireland, results in a rapid transformation of a forested landscape into an open one. It can impact forest fauna with the process of harvesting itself causing considerable disturbance to ecosystems and changes to the physical environment (Larsen 1995). The low mobility of slugs (Strayer et al. 1986) and their susceptibility to dehydration (Prior 1985) mean that changes in microclimate can also have an adverse effect on populations in disturbed areas. In addition, slug assemblages have been found to be sensitive to forestry management (Nystrand and Granström 1997; Kappes 2006; Rancka et al. 2015). In particular, Strayer et al. (1986) suggest that disturbances (through forest fires, clear-felling or agricultural cropping) in forests in New England, USA, could reduce gastropod densities with some species becoming extinct at a local scale as a result. However, they also suggest that recovery of gastropods post disturbance is rapid. Nevertheless, Platts and Speight (1988) noted that forestry operations in Portugal appear to have eradicated *G. maculosus* from sites in which it was previously found although no time scale is given in this regard. For these reasons, the presence of this protected species in commercial conifer plantations in Ireland is of concern. Listed among current threats to the species are forest planting on open ground, forest replanting and forestry clearance (NPWS 2013). Nevertheless, the National Parks and Wildlife Service (NPWS), in its 2013 Article 17 report to the EU on the conservation status of Irish species and habitats, states that *G. maculosus* is “resilient” to clear-felling despite its short-term negative impact (NPWS 2013). However, this statement, primarily based on preliminary studies (Mc Donnell and Gormally 2011; Reich et al. 2012), is qualified by the recommendation that more data are required regarding the temporal occupation of woodland by the species in addition to its responses to forestry operations (NPWS 2013). The absence of comprehensive population estimates for *G. maculosus* is also highlighted (NPWS 2013).

Only one study, to date, has investigated *G. maculosus* population sizes in clear-fell and mature conifer stands (Reich et al. 2017). The study, undertaken in a single plantation, recorded significantly lower catches of *G. maculosus* in a clear-felled stand (felled five years prior to the study) than in mature plantations. Since no data regarding *G. maculosus* catches prior to felling were available for the study, Reich et al. (2017) recommended that a before-after-control-impact assessment of the species be undertaken in future investigations given forestry manager obligations to protect *G. maculosus*. This is particularly urgent since current forestry guidelines for commercial forests in Ireland (published prior to the discovery of *G. maculosus* in commercial conifer plantations) do not list the potential impact of forestry practices on the species (Forest Service 2009).

In the Republic of Ireland, Coillte—The Irish Forestry Board Limited (a commercial company with the government as a shareholder) owns approximately 54% of the national forest estate (DAFM 2016). It currently holds the Forest Stewardship Council (FSC) certification, which requires that its forests be managed with consideration for ecosystems and biodiversity (Principle 6, FSC 2016). Given the current gaps in the knowledge and Ireland's obligations under the EU Habitats Directive coupled with the commitment of Coillte to FSC certification, further study is urgently required. To address these gaps, this study aims the following:

1. To compare *G. maculosus* captures across mature, exotic Sitka spruce-dominated plantations, previously clear-felled stands and adjacent peatland habitats;
2. To determine the suitability, for forest managers, of population estimate models for *G. maculosus*; and
3. To assess the implications of felling by comparing relative abundances of *G. maculosus* directly before and after the clear-felling of a mature, exotic Sitka spruce-dominated plantation.

2 Materials and methods

2.1 Study areas

Four study sites (1–4) consisting of commercial Coillte-owned forestry plantations and adjacent peatland areas within the distribution range of *G. maculosus* in the south-west of Ireland were chosen in 2014. The study sites (12–40 km apart) were those where clear-felling of at least one stand of mature plantation was scheduled to take place within the lifetime of the project and where *G. maculosus* was known to be present.

Ten mature (predominantly Sitka spruce) plantation stands distributed among four sites (2–3 stands per site) were selected (Table 1). The stands (hereafter referred to as MP) were planted by Coillte on peatland in the early 1970s (Coillte 2014) and were of felling age at the start of this study. Originally two stands (a and b) were selected with stand "a" acting as control and stand "b" scheduled for felling within the lifetime of the project (July 2014 to October 2015). However, due to changes in the felling schedule caused by Storm Darwin in February 2014, the impact assessment using Before-After-Control-Impact-Paired (BACIP) analysis was limited to just one of the four planned MP stands scheduled for felling (i.e. stand 2b). Two additional stands (2c and 3c) were included in the study as back-ups in the event of further changes to the felling schedules. However, none of the remaining or additional sites were felled in sufficient time to allow a before and after comparison. Therefore, the data from stands 2c and 3c were subsequently incorporated in the MP data set (total number of MP stands = 10). Four previously clear-felled stands (hereafter referred to as PCF) (1 stand per site) were also selected. These had been felled in 2013 prior to the start of the project and at the time of the study were dominated by *Picea sitchensis* tree stumps interspersed with, inter alia, *Digitalis purpurea* L., *Juncus effusus* L. and mosses. Four adjacent areas of peatland (hereafter referred to as PL) (1 adjacent peatland per site) were also selected. Vegetation in the peatlands was dominated by *Molinia caerulea* (L.) Moench and *Calluna vulgaris* (L.) Hull.

2.2 Sampling design

Two sampling methods (details given below) were utilised in this study, namely sampling using refuge traps (July 2014–November 2015) and searching by hand (June–September 2015). For the trapping method, a sample of nine trees (3 × 3), at least 10 m from the edge of the forest, was selected in each mature forest stand. Mature forest stands within sites were situated between 200 m and 900 m apart to prevent any potential crossover of populations between stands—this is based on a study by Mc Donnell and Gormally (2011) who found that just 3.85% of slugs marked on a woodland tree had travelled between 9.25 m and 14.2 m (after 64 days) to another tree. A single refuge trap (De Sangosse, Pont du Casse, France, hereafter referred to as "trap") was fixed to the north side of each tree (using nails and string) at 1.5 m above ground level after Mc Donnell and Gormally (2011). The traps consist of three layers: a perforated plastic layer, a padded fabric layer to retain moisture, and a metallic foil outer layer (Johnston et al. 2017). Refuge traps which measured 0.5 × 0.5 m permitted the calculation of numbers of catches per square metre. While Johnston et al. (2017) demonstrated that traps placed

Table 1 Management history of mature plantation (MP) stands (a, b and c) at four sites[1,2]

Site	Stand	Number of thinnings	Years since last thinning	Age of stand	Yield class
1	a	2	10	45	16
1	b	3	10	44	14
2	a	4	4	44	16
2	b[3]	3	3	43	12
2	c	3	3	43	12
3	a	3	6	43	18
3	b	3	7	43	18
3	c	3	6	43	16
4	a	1	8	43	16
4	b	1	9	44	12

[1] Source: Coillte 2014; a, b and c refer to stands designated as controls (a), stands designated for felling during the study (b) and additional stands as "back-ups" in the event of unpredicted changes to felling schedules (c)

[2] Coillte stands are on average 19 ha in size (Coillte 2014)

[3] The sole forest stand which was subjected to a clear-felling event during the course of this study

near the base of trees result in fewer catches than traps placed on trees at 1.5 m above ground level, it was not possible (for reasons of health and safety in combination with time constraints) to place traps further up the trees. In clear-fell stands, individual traps (secured using nails and string) were placed on the north side and top of nine (3 × 3) tree stumps (18–27 cm high) situated at least 10 m from the stand edge. At peatland sites, nine traps were placed on rocks using methods described by Mc Donnell and Gormally (2011) for *G. maculosus* sampling on rock outcrops in peatland. In addition, in each habitat (at a minimum distance of 45 m from the tree, stump or rock traps), nine (3 × 3) traps (1.5 m apart) were secured (using tent pegs) over vegetation/bare soil on the ground between trees, tree stumps and rocks. These traps (hereafter referred to as "ground traps") were deployed because Mc Donnell and Gormally (2011) showed that *G. maculosus* moves between trees and along the forest floor. While protocols using traps follow those of Mc Donnell and Gormally (2011), additional sampling methods (i.e. hand searching, described in Section 2.4) were undertaken over four months (June to September 2015) to allow for any possible variation in trapping efficiency across habitats. Shortly before the tree felling event took place at site 2b during the course of this study, traps were removed for health and safety reasons. These traps were then replaced on the remaining stumps, in the newly clear-felled stands (hereafter referred to as NCF) following the removal of logs from the site.

2.3 Mark-recapture studies

Once a month (over a 16-month period), slugs were marked every day (hereafter referred to as sampling days) over five consecutive days (hereafter referred to as sampling weeks) based on recommendations by Reich (2015), Reich et al. (2017) and Kendall and Bjorkland (2001) to ensure a robust design. This decreases bias and allows for a more efficient estimate of population dynamics. On each of the sampling days, all of the traps were checked at every site and in every habitat. For the purposes of this study, slugs greater than 1 cm in diameter when rolled into a defensive ball are referred to as "adults" (based on the size categories from Reich 2015) and hence large enough to be tagged. Smaller slugs (too small to tag effectively) were considered sub-adults and are hereafter referred to as "juveniles." Confirmation by dissection to determine sexual maturity was not an option in this live population study. In addition, weight could not be used as an effective determinant of maturity in the field since humidity levels are known to affect the weight of slugs (A O'Hanlon, *pers. comm.*).

The marking strategy for this project was based on that developed by Mc Donnell and Gormally (2011). The Visible Implant Elastomer (VIE) (Northwest Marine Technology, Shaw Island, Washington) in nine different colours was used to mark adult slugs. VIE is a medical-grade, silicone-based material which in this study was mixed with a curing agent and injected as a liquid after which it cured into a pliable, biocompatible solid (Northwest Marine 2015). Marks for the different months were distinguished from each other based on different colours and locations of tags. For the initial nine months, from July 2014 to March 2015, tags were inserted into the left-hand side of the foot from the head down to the tail. For the final seven months, from April to October 2015, the tags were placed into the right-hand side of the foot from the tail to the head. The colour location was reversed for slugs caught in ground traps to distinguish them from those caught in tree traps. To check for the presence of tags in captured individuals, each slug was lightly pressed against a clear piece of plastic and a torch emitting a deep purple light (405 nm) (Northwest Marine Technology, Shaw Island, Washington) was then shone over the individual.

The torch is designed to cause red, orange, blue, yellow, green, and pink VIE to fluoresce, making tags easier to observe, particularly in poor light conditions. The remaining three colours which were used, i.e. brown, black and purple, do not fluoresce. Every adult *G. maculosus* found was checked for any previous tags, recorded and marked with the relevant colour for the sampling month. Any juvenile slugs caught were also recorded to provide information on juvenile activity levels. Slugs were then returned to the relevant trap. Damaged traps were replaced as required.

2.4 Hand searching

Johnston et al. (2017) found that hand searching was more effective than traps in clear-fell stands particularly after rain when slugs emerged and became active. Traps also tended to dry out in open clear-fell stands thereby rendering them less attractive to slugs unlike traps under the shade of trees in mature plantations. For this reason, hand searches were also undertaken for a limited period (June and September 2015) at mature forest/clear-fell stands and peatland areas at a distance of 45 m from all other trapping locations. Hand searches were completed on nine trees in mature forest stands, nine stumps in the clear-fell stands and over a marked area of similar size (5 m × 5 m) in peatland. Hand searches for both adult and juvenile *G. maculosus* were undertaken by two people for 5 min per person in each of the designated areas, giving a total of 10 min searching for each sampling day. Searches consisted of examining tree trunks (to a maximum height of approximately 2 m), tree stumps and rocks in addition to examining the areas in between these features, thereby surveying all likely refuges in each habitat. Slugs found during hand searching were not tagged.

Tree circumference at breast height (1.5 m) and at the base of trees was recorded using a flexible tape measure. Percentage cover of moss from ground level to 1.5 m on tree trunks was also recorded. Data regarding MP management such as year of planting were provided by Coillte (2014) (Table 1).

2.5 Data analysis

All analyses were undertaken using SPSS version 21 except for population estimates (Jolly-Seber and Schnabel models) which were calculated using Excel through formulae described by Krebs (1999) and Greenwood (1996). The Jolly-Seber model allows for an "open" population where the number of animals varies (due to immigration, emigration, birth and death), while the Schnabel model is based on the assumption of a "closed" population i.e. no emigration or immigration of the population takes place during the period of study (Krebs 1999). In the comparisons of habitats and direct comparisons between control and impact stands, where assumptions of normality and homogeneity of variance were violated, Welch's *t* test or Welch's ANOVA was used followed by a Games-Howell post-hoc test to determine pair-wise differences where more than two groups were examined. Correlations were determined using Spearman's rank correlation. The Before-After-Control-Impact-Paired (BACIP) analysis (Smith 2002) was carried out using an independent samples *t* test on the differences between control and impact sites before and after the impact (i.e. clear-felling).

3 Results

3.1 Comparison of *G. maculosus* catches in mature plantation (MP) stands, previously clear-felled (PCF) stands and adjacent peatland (PL)

Catches are reported as mean catch number per sampling day for all MPs, all PCFs and all PLs to allow for comparison across the different habitat types over the 16 months of sampling (Table 2). The stand subjected to a clear-felling event during the course of this study (site 2b) was not included in these analyses. The mean number of adult *G. maculosus* catches per sampling day using traps was greatest in MPs (5.23), followed by PLs (0.50) and PCFs (0.47). Significant differences were found between MPs and PCFs and between MPs and PLs ($P < 0.001$ and $P < 0.001$ respectively, Welch's ANOVA followed by Games-Howell post-hoc analysis). The mean number of juvenile catches, while considerably lower than those for adults, was also greatest in MPs (0.47), followed by PLs (0.24) and PCFs (0.047). Significant differences were found between all three habitats (Table 2).

Both with and without the addition of hand search data, the mean number of adult *G. maculosus* caught (June–September 2015) was still greatest in mature forest stands, followed by PCFs and PLs with significant differences between MPs and PCF/PL (Table 3). However, numbers of adult specimens found in PCFs when hand searching was included were 3.8 times greater than where hand searching was not employed with a significant difference found between the two sampling strategies ($P < 0.001$, Welch's *t* test). The mean number of juveniles was also greatest in the MPs, but there was an 18-fold increase in the mean number of juvenile specimens found in the PCFs when hand searching data were included (Table 3) with a significant difference found between the data including and excluding hand searches ($P = 0.015$, Welch's *t* test). No significant difference, however, was found between data including and excluding hand searches for the MPs and PLs for both adults ($P = 0.766$, $P = 0.890$ respectively, Mann-Whitney *U*-test) and juveniles ($P = 0.881$, $P = 0.953$ respectively, Mann-Whitney *U*-test).

3.2 Population density estimates

Jolly-Seber estimates could not be calculated for any sampling weeks in PCFs and PLs due to low numbers of recaptures

Table 2 Comparison of *G. maculosus* catches across nine mature plantation stands (MP), four previously clear-felled forest stands (PCF) and four adjacent peatlands (PL) using traps (July 2014–October 2015) placed on tree trunks, stumps and rocks, respectively, in addition to ground traps[1]

	MP	PCF	PL
No. of sampling days (N)	585	320	305
Mean no. of adults/day (±SE)[2]	5.23 (±0.24)	0.47 (±0.05)	0.50 (±0.06)
P values			
MP	–	–	–
PCF	0.000	–	–
PL	0.000	0.957	–
Mean no. of juveniles/day (±SE)[3]	0.47 (±0.05)	0.047 (±0.01)	0.24 (±0.04)
P values			
MP	–	–	–
PCF	0.000	–	–
PL	0.001	0.000	–

Adult: Test statistic = 190.4; df = 2; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between habitats, Games-Howell multiple-comparison test; juvenile: test statistic = 45.091; df = 2; $P = <0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between habitats, Games-Howell multiple-comparison test

[1] Data from stand 2b which was subjected to a clear-felling event during the course of the study are not included in this table

[2] Individuals > 1 cm (diam.) when rolled into a defensive ball

[3] Individuals < 1 cm (diam.) when rolled into a defensive ball

(estimates are only considered to be accurate when the number of recaptured animals over the sampling week is greater than ten (Greenwood 1996)). Within the MPs, estimates using the Jolly-Seber method could only be calculated for six sampling weeks (out of a total possible 98) due to either low recaptures (less than ten) or a failure of the Jolly-Seber goodness-of-fit test (Sutherland 1996). Of these six estimates, only those at two MP stands, 2a and 3c (density of 0.7 individuals/m^2 and 1 individuals/m^2, respectively), could be calculated during April 2015 when the overall goodness-of-fit was satisfactory. As with the Jolly-Seber method, population size estimates using the Schnabel method could not be calculated for PCF and PL habitats due to low capture numbers. However, the Schnabel model was found to be a good fit in MPs for 33 out of 135 sampling weeks. Estimates could not, however, be calculated for two of the MP stands (2c and 4b) due to low capture numbers (Fig. 1). For the same reasons, estimates could not be calculated in July 2014, January 2015, June 2015 or September 2015 for the remaining eight stands (Fig. 2). Mean (±SE) Schnabel population density estimates in the

Table 3 Comparison of *G. maculosus* catches across nine mature plantation stands (MP), four previously clear-felled forest stands (PCF) and four adjacent peatlands (PL) using traps only (Tr) and traps in combination with hand searching (Tr&Hs) (June–September 2015) with traps placed on tree trunks, stumps and rocks respectively, in addition to ground traps[1]

	MP		PCF		PL	
	Tr	Tr&Hs	Tr	Tr&Hs	Tr	Tr&Hs
No. of sampling days (N)	135	135	80	80	80	80
Mean no. of adults (±SE)[2]	3.68 (±0.4)	3.93 (±0.37)	0.56 (±0.1)	2.13 (±0.4)	0.53 (±0.09)	0.58 (±0.10)
P values						
MP	–	–	–	–	–	–
PCF	0.000	0.001	–	–	–	–
PL	0.000	0.000	0.960	0.000	–	–
Mean no. of juveniles (±SE)[3]	0.71 (±1.22)	0.73 (±1.24)	0.02 (±0.02)	0.36 (±0.15)	0.16 (±0.05)	0.21 (±0.06)
P values						
MP	–	–	–	–	–	–
PCF	0.000	0.115	–	–	–	–
PL	0.000	0.000	0.026	0.614	–	–

Adult: test statistic Tr = 38.7; test statistic Tr&Hs = 44.5; df = 2; $P < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between habitats, Games-Howell multiple-comparison test; Juvenile: test statistic Tr = 23.9; test statistic Tr&Hs = 8.7; df = 2; $P = < 0.001$, Welch's ANOVA. *P* values given in bold indicate significant differences between habitats, Games-Howell multiple-comparison test

[1] Data from Site 2b which was subjected to a clear-felling event during the course of the study are not included in this table

[2] Individuals > 1 cm (diam.) when rolled into a defensive ball

[3] Individuals < 1 cm (diam.) when rolled into a defensive ball

mature plantations ranged from 9.61 (±3.3) individuals/m^2 to 23.49 (±12.2) individuals/m^2 with mean number of individuals captured (excluding recaptures) over the sampling week and mean total catch per sampling day following similar patterns (Fig. 1). Discounting occasions where estimates could not be calculated, the mean (±SE) Schnabel population density estimate per square metre in each month ranged from 24.4 individuals/m^2 (±6.4) in August 2014 (week 2) to 4.5 individuals/m^2 (±0) in February 2015 (week 8) (Fig. 2). Significant positive Spearman's rank correlations were found in MPs between Schnabel population density estimates and mean total catch of *G. maculosus* per sampling day ($P < 0.004$, $r_s = 0.490$) (Fig. 3a) and between Schnabel population density estimates and numbers of captures (excluding recaptures) during sampling weeks ($P < 0.001$, $r_s = 0.891$) (Fig. 3b). When captures for each of the sampling days (1 to 5) were averaged for the MPs over the length of the study, the mean percentage of marked individuals in each catch increased over time so that by day five a mean of 60% of captures consisted of marked individuals (Fig. 5 in Appendix). Overall, the average percentage (±SE) of unmarked individuals was 25% (±1%) of the catch in MPs, 59% (±2%) in PCFs and 54% (±1%) in PLs.

3.3 Before-After-Control-Impact-Paired (BACIP) assessment

As population estimates could not be calculated in NCF due to low numbers, BACIP analysis was carried out using total catches per sampling day to allow for comparison post-impact (i.e. after a clear-felling event). Mean number of individuals per sampling day (±SE) caught over two sampling weeks before felling in the control and impact stands (2a and 2b, respectively) were 6.9 (±2.7) and 6.3 (±1.3), respectively. No significant difference was found between the control and impact stands prior to felling ($P = 0.848$, Welch's t test). Felling and forwarding (i.e. hauling of logs to roadside) was undertaken over five months (Fig. 4) during which time, for health and safety reasons, no sampling took place. The traps were replaced in February 2015 onto the remaining stumps of the trees which were sampled prior to the clear-felling event, and two weeks later, the first catches (post clear-felling) were recorded. The mean number of individuals per sampling day (±SE) over the eight months following trap replacement in the impact stand was 0.3 (±0.1), while the corresponding months in the control stand had a mean (±SE) of 6.2 (±0.8) with a significant difference found between the two stands ($P < 0.001$, Welch's t test). None of the individuals captured over two sampling weeks in the impact stand prior to felling were recaptured during eight sampling weeks post-felling in contrast to a 21% recapture rate at the control stand over the same timeframe. The other three MP stands sampled (1a, 4a, 4b) during the same period yielded a mean recapture rate of 38% (±5.4% SE). In addition, in post-impact sampling weeks, numbers were consistently lower in the impact stand than those in the control stand, even when 10 min hand searches were included (Fig. 4). A BACIP analysis confirmed a significant impact from the felling event using data from trap catches only, as well as data combining trap and hand searching catches ($P = 0.015$ and $P = 0.014$, respectively, independent samples t test).

3.4 Stand characteristics

Across nine MPs, significant, moderate, positive Spearman's rank correlations were found between average catch of adult *G. maculosus* per tree and circumference at the base of the tree ($P < 0.001$, $r_s = 0.369$; $N = 81$), as well as circumference at breast height ($P = 0.015$, $r_s = 0.286$; $N = 81$). No significant correlation was found between average catch of adult *G. maculosus* per tree and the percentage moss cover ($P = -0.58$, $r_s = 0.626$; $N = 81$).

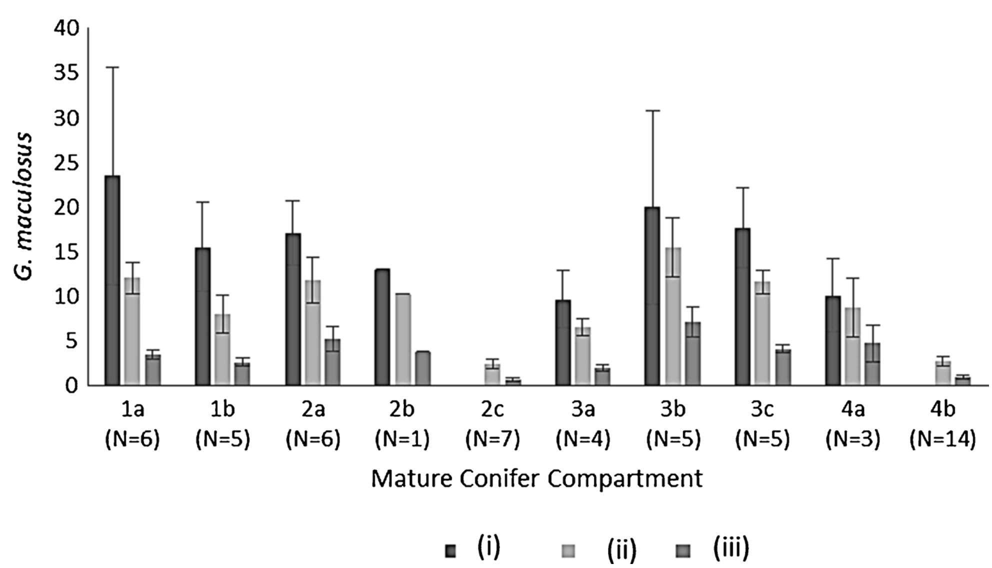

Fig. 1 Mean (means are calculated on the basis of the number of sampling months for which Schnabel population estimates could be calculated (i.e. N)) (±SE) *G. maculosus* in mature plantation (MP) stands over a period of sixteen months (July 2014–October 2015): (i) mean Schnabel population estimates; (ii) mean number of individuals captured per metre (while (i) that stands for 2c and 4b could not be calculated due to low capture numbers and/or lack of fit, (ii) and (iii) are presented) (excluding recaptures) over sampling week; (iii) mean of average total catch per day

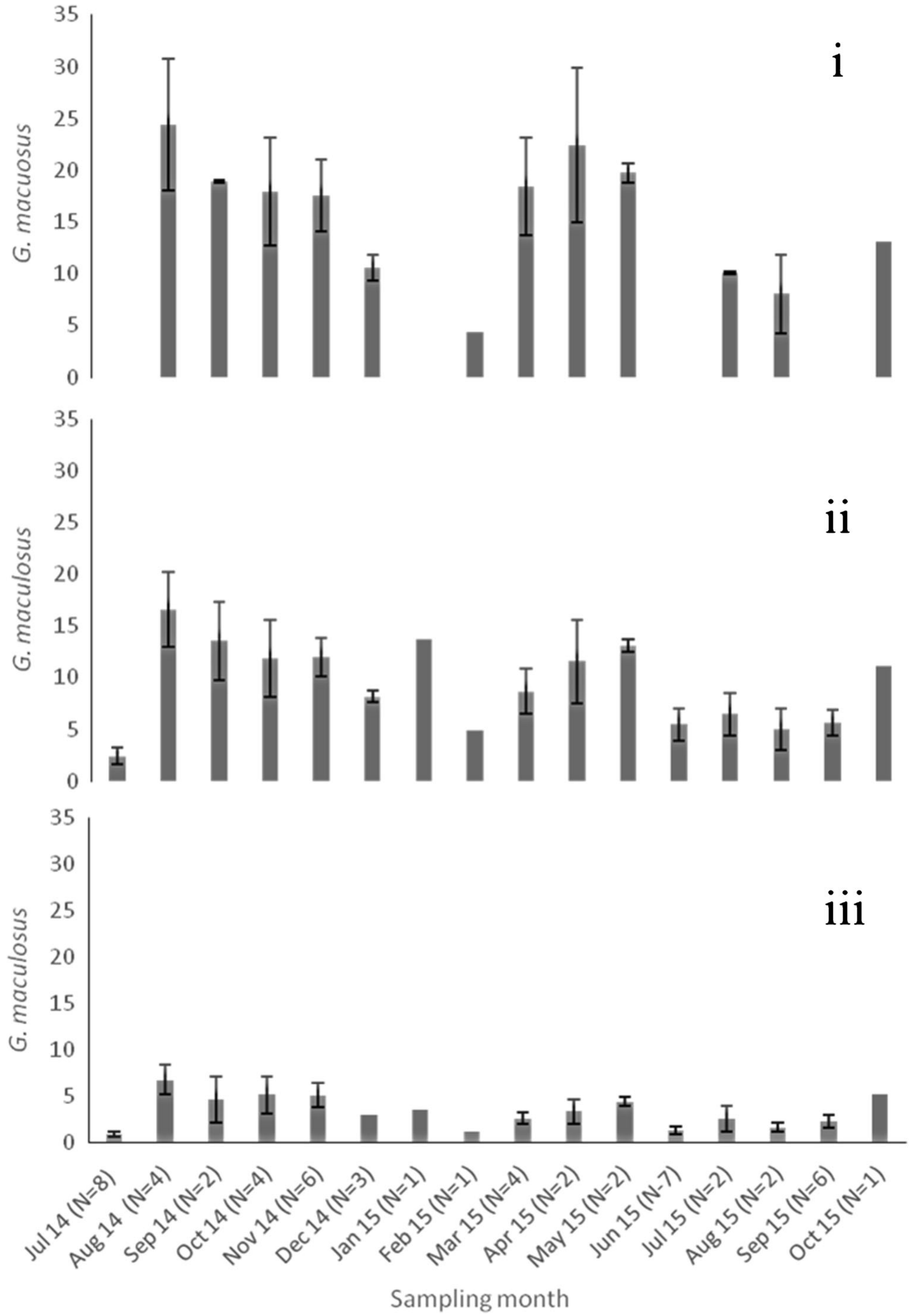

Fig. 2 Mean (means are calculated on the basis of the number of MP stands for which Schnabel population estimates could be calculated (i.e. N)) (±SE) *G. maculosus* in mature plantation (MP) stands for each month from July 2014 to October 2015: (i) mean Schnabel population estimates; (ii) mean number of individuals captured per metre (while (i) for July (2014) and January/June/ September (2015) could not be calculated due to low capture numbers and/or violation of the goodness-of-fit, (ii) and (iii) are presented) (excluding recaptures) over sampling week; (iii) mean of average total catch per day

4 Discussion

4.1 Comparison of *G. maculosus* catches in mature plantation stand, previously clear-felled stands and adjacent peatland

Given that peatland has been considered historically as a natural habitat for *G. maculosus* (Platts and Speight 1988), it is surprising to find greater catches in mature plantation and previously clear-felled stands. While these results are likely to reflect actual numbers found within the stands, it is important to consider trapping efficacy across the three habitat types. Johnston et al. (2017) found that the area under traps on tree stumps in previously clear-felled stands tends to be drier in comparison to those in mature plantations and the adjacent peatland. The shape of tree stumps means that it is not possible to attach traps as tightly to the stump surface and sides as it is on the tree trunks and rocks found in mature

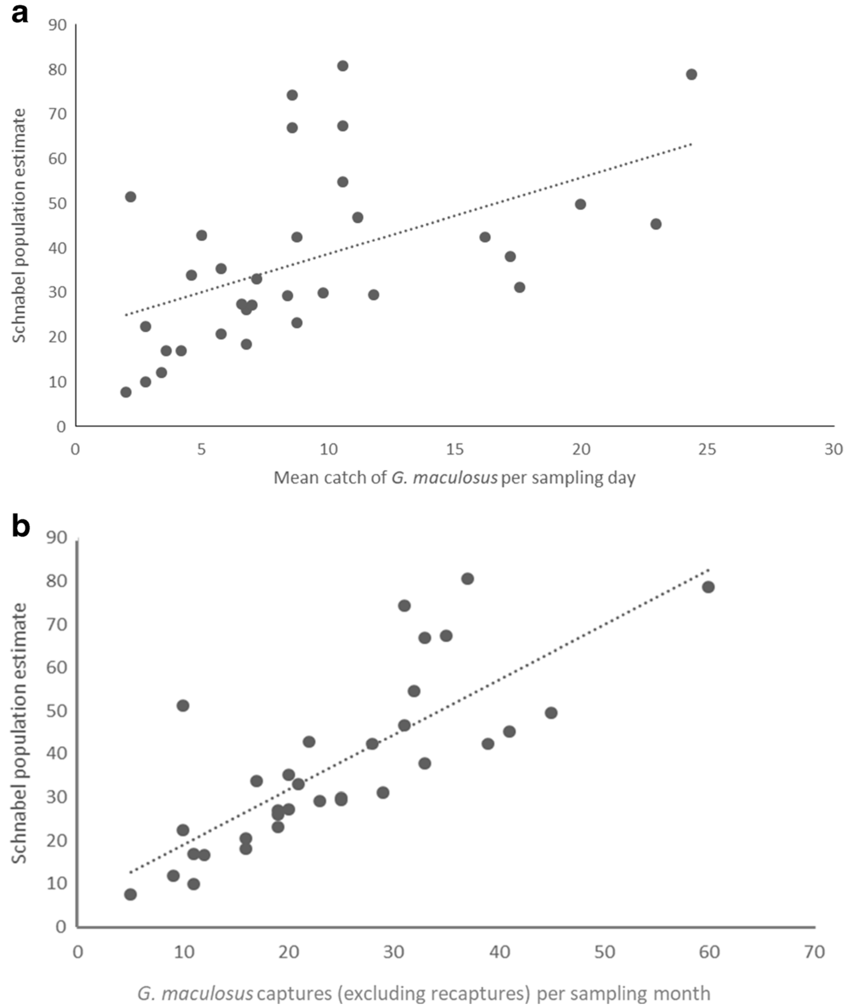

Fig. 3 Relationship between Schnabel population estimates (July 2014–October 2015) and: (**a**) mean total catch of *G. maculosus* per sampling day in eight mature plantations (MP; $N = 33$); (**b**) *G. maculosus* captures (excluding recaptures) per sampling month in eight mature plantations (MP; $N = 33$)

plantations and the adjacent peatland, respectively. It is likely that runoff from rainfall in mature plantations and the adjacent peatland enters the narrow space between the trap and the surface to which it is attached thereby maintaining damp conditions under the traps. In mature plantations, tree shading will further delay drying of the traps. Clearly, drier traps would be less attractive to slugs seeking to avoid dehydration, and the greater numbers of slugs captured in the previously clear-felled stands by hand collecting in addition to refuge trapping versus traps alone supports this hypothesis. These findings emphasise the importance of undertaking hand searching in addition to using refuge traps, particularly in clear-felled areas, when assessing sites for *G. maculosus* as suggested by Johnston et al. (2017). Given the consistently greater numbers of *G. maculosus* found in mature plantations, conservation efforts should focus more on commercial forestry to ensure adequate future protection of the species. Although Johnston et al. (2017) hypothesised that *G. maculosus* moves up the tree to forage, no study has, to date, examined the distribution of the species higher in the canopy. It is, therefore, still unknown how much of the tree and associated microhabitats is used by the species. The impact of this on trapping efficiency and density estimates, while outside the scope of this study, requires further investigation.

4.2 Population density estimates

Krebs (1999) describes the Jolly-Seber model as a method of population estimation for open populations, which allows for births, deaths, immigration and emigration. As the Jolly-Seber method is generally unreliable without at least ten recaptures (Greenwood 1996), its use was limited in this study because many sampling occasions, particularly those in previously clear-felled stands, newly clear-felled stands and peatland habitats, had to be eliminated due to a failure to meet this requirement. In addition, the method requires that there is some permanent emigration (Sutherland 1996), but high recapture rates in mature plantation stands (when taken over the entire length of the study) could indicate a degree of "trap-happiness" thereby weakening this assumption. The continual recapturing of individuals over several succeeding

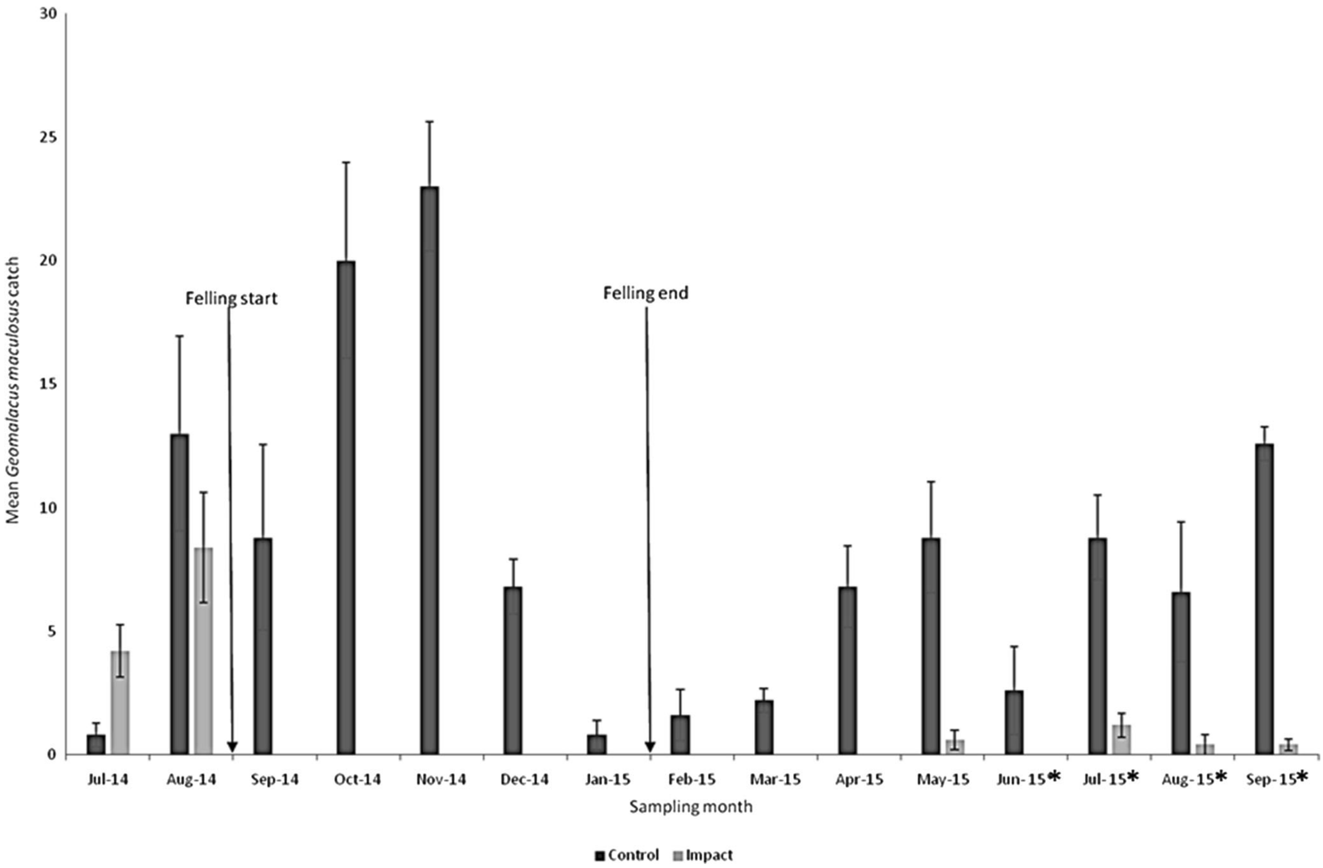

Fig. 4 Mean (±SE) number of catches of adult *G. maculosus* per sampling day in the control and impact stands over 15 months between July 2014 and September 2015. Traps were removed from the impact site during felling for health and safety reasons. *Months where hand searching data were included

months in the mature plantations suggests that the dispersal rate of the individuals was relatively low, likely due to movement predominantly occurring up and down the tree as opposed to between trees. Lack of movement between trees, at least at ground level, is supported by low numbers of catches found under traps placed on the forest floor (Johnston et al. 2017).

While the Schnabel population estimate assumes that a population is closed (Alcoy 2013), the advantage of using this estimate is that the low level of dispersal of individuals in the population fits closest to this model. However, it was still not possible to obtain population estimates in previously clear-felled stands, newly clear-felled stands and peatland habitat. This was because there were either no recaptures to calculate the estimate or the Schnabel goodness-of-fit test was violated. The Schnabel estimates in the mature plantations, however, correlate with both the mean total catch per sampling day and the number of captures (excluding recaptures) over the sampling week. Therefore, total captures reflect well the actual population estimates as determined by the Schnabel method despite the limitations of the method. Activity in terrestrial gastropods is associated with a number of environmental factors (Young and Port 1989), and (apart from July 2014 at the start of the study) greater proportions of unmarked *G. maculosus* individuals were present in the warmer months from April to August than in the colder months which is reflected in Johnston et al. (2017) who found greatest catches in summer and autumn months. When the proportion of unmarked individuals was averaged over sampling days, 60% of the catch on the last sampling day (day 5) consisted of recaptured individuals entering the traps. It is likely that individuals that were previously deemed too small to tag may have entered the appropriate size class in later months, which may have contributed to the percentage of unmarked individuals. Nevertheless, the majority of individuals were captured over five consecutive sampling days in mature plantation stands. The Schnabel population size estimates calculated also correlate with the mean total catch per day of *G. maculosus* adults. Since calculating population size estimates using mark-recapture is labour-intensive and requires specialist training and equipment, it is unlikely that this will be adopted by foresters in conservation strategies for the species. However, the use of mean total catch per day as a proxy for foresters undertaking surveys to estimate population sizes of *G. maculosus* in mature conifer plantations, at least in the south-west of Ireland, may provide a more feasible solution.

4.3 Before-After-Control-Impact-Paired (BACIP) assessment

It is important to note that, due to the re-scheduling of felling operations as a result of Storm Darwin in February 2014, only one of the original four selected stands of mature conifers was felled with sufficient time to allow sampling before and after the impact event. While it would be inadvisable to make generalisations on the basis of a single felling event, the results are discussed given that this is the first ever BACIP assessment for *G. maculosus* and the results can be used to inform the design of future replicated trials. Mean catch per sampling day post-felling at the impact stand dropped by 95% compared to only a 10% drop in the control stand. These results reflect the findings of Strayer et al. (1986) who reported that disturbances (including clear-felling) may reduce densities of gastropods. Individuals tagged prior to felling were not present post-felling at the impact site unlike the control site where 21% of tagged slugs were subsequently recaptured. While it is possible that those few individuals found within the impact stands post-felling had colonised from nearby habitats, the effect of surrounding stands harbouring *G. maculosus* on the colonisation of clear-felled stands requires further investigation particularly given the low dispersal ability of *G. maculosus* within habitats (Mc Donnell and Gormally 2011).

4.4 Influence of stand characteristics

Significant, moderate, positive correlations were found between the average catch of adult *G. maculosus* per tree in the mature plantation stands and circumference of the tree at both the base and at breast height. This correlation mirrors that found by Reich et al. (2012) who hypothesised that this was due to the association of greater bryophyte cover on older trees with larger circumference at breast height. However, unlike Reich et al. (2012), species catch across a range of mature plantation stands did not correlate with percentage moss cover. As terrestrial gastropods are known to avoid exposure to unfavourable conditions (Rollo 1982) and evade cold temperatures by moving below ground (Cook 2004), it is likely that *G. maculosus* makes use of the base of the tree as a refuge during non-optimal weather conditions. Indeed, the authors have observed *G. maculosus* sheltering at the base of trees throughout the study period. This suggests that while *G. maculosus* makes use of bryophytes as a source of both food and shelter (Platts and Speight 1988), the association with larger tree circumference, particularly at the base of the tree, may be of greater importance for the species as a larger circumference would allow for a greater number of slugs to shelter.

4.5 Conclusions

Of the three habitats investigated in this study, the greatest number of *G. maculosus* captures occurred in mature plantations, highlighting the importance of protecting the species where it occurs in commercial forestry. In addition, the greater catches of *G. maculosus* associated with economically more valuable forest stands (i.e. trees of greater circumference) in commercial forestry is not compatible with current forestry practices in Ireland where clear-felling and removal of such stands is the norm. BACIP analysis, albeit at a single location, shows a significant impact of clear-felling on *G. maculosus* captures with a 95% reduction in catches post-felling. Further replicated trials are required to determine whether this accurately reflects the impacts of clear-felling at other forests where *G. maculosus* is found. In addition, studies examining longer term impacts are needed followed by an examination of impacts during the forest cycle i.e. replanting, fertiliser/herbicide use and thinning. Current legislation under the Habitats Directive requires Member States to prohibit, among other factors, the "deterioration or destruction of breeding sites or resting places" of an animal species (such as *G. maculosus*) listed in Annex IV in its natural range. Under the Irish legislation, *G. maculosus* is protected wherever it occurs. This study has shown that total catches correlate well with population estimates which now provide a quick and easy sampling method for monitoring populations in a wider array of sites. However, this study, in the context of legislative obligations, also indicates the need for practical mitigation measures. Two possible measures include the retention of small stands of forestry (Raivio et al. 2001) and the translocation of the species (Germano et al. 2015). While a short-term study undertaken in Co. Galway by Reich et al. (2012) demonstrates the possible benefits of retaining 3-m stumps post-clear-felling, the long-term benefits to *G. maculosus* have not yet been assessed. In addition, the benefits or otherwise of translocation have not yet been quantified for this species, and therefore, it is not possible to speculate on this as a measure without further research into both the carrying capacity of forests and the ability of *G. maculosus* to acclimatise to new areas. Further research is, therefore, urgently required to determine practical mitigation measures to protect the species where it occurs in commercial forestry.

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Appendix

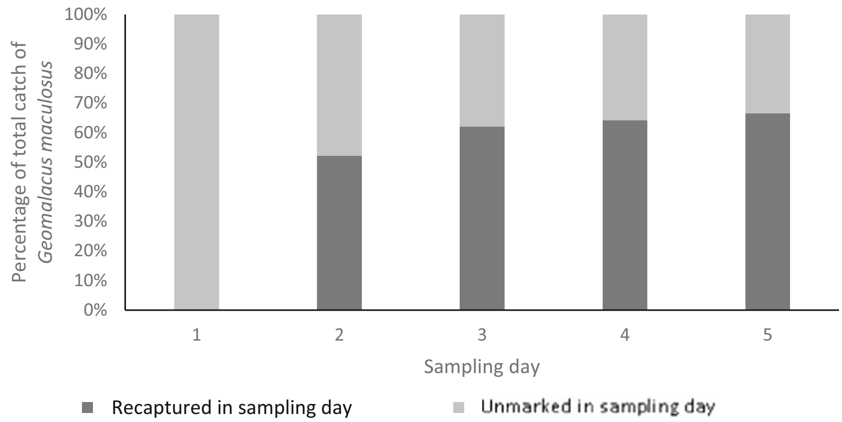

Fig. 5 Mean percentage of total catch of *G. maculosus* per sampling day ($N = 117$) consisting of individuals recaptured at least once during the sampling week in mature plantations (MP) (July 2014–October 2015)

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