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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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Article

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1   Mature exotic conifer stands have greater catches of the EU-protected Geomalacus maculosus than adjacent

2   peatland or clear-felled stands - implications for forestry.

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10   **Short title:** G. maculosus in commercial forestry plantations

11   **Key words:** conservation, capture-mark-recapture, population estimates, Before-After-Control-Impact-Paired

12   (BACIP)

13   **Contribution of the co-authors**: Erin Johnston undertook the fieldwork, analysed the data and wrote the

14   manuscript. Gesche Kindermann assisted with site selection and fieldwork, and edited the manuscript. Jack

15   O'Callaghan, Daniel Burke, Cillian McLoughlin and Sinéad Horgan contributed to data collection and assisted

16   with fieldwork. Inga Reich assisted with population estimates, and gave advice on tagging G. maculosus. Rory

17   Mc Donnell provided specialist advice, assisted with site selection / experimental design and edited the

18   manuscript. Christopher Williams provided statistical advice and edited the manuscript. Michael Gormally

19   designed and supervised the project and acted as senior editor for the manuscript.

31 **Key Message Mature exotic Sitka spruce dominated stands, particularly trees of greater circumference,**

32 **result in greater numbers of Geomalacus maculosus captures than adjacent clear-felled stands and**

33 **adjacent peatland with Before-After-Control-Impact-Paired analysis indicating lower catches of G.**

34 **maculosus post-felling.**

35 **Context** The discovery of EU-protected Geomalacus maculosus in commercial plantations requires an

36 understanding of the implications of forestry practices on the species within the context of sustainable forest

37 management.

38 **Aims**

39 1. Compare Geomalacus maculosus captures across mature exotic Sitka spruce dominated stands, previously

40 clear-felled stands and adjacent peatland habitats.

41 2. Assess the suitability, for forest managers, of population estimate models for G. maculosus.

42 3. Assess implications of felling by comparing relative abundances of G. maculosus directly before and after

43 clear-felling at a mature exotic Sitka spruce dominated stand.

44 **Methods** Geomalacus maculosus catches were compared at four sites across two to three mature (43-45 years

45 old) conifer stands per site, one clear-felled stand per site and one adjacent peatland per site using metric traps

46 and hand-searching. Capture-mark-recapture studies were undertaken to estimate population sizes. A BACIP

47 (Before-After-Control-Impact-Paired) analysis was undertaken in one forest stand at one forest site to determine

48 impacts of a clear-felling event.

49 **Results** Mean catches of Geomalacus maculosus adults in the mature forest stands were over 10 and 11 times

50 greater than mean catches on peatland and clear-fell stands respectively. The Schnabel model for estimating

51 population size was most suited for mature forest stands but could not be utilised for other habitats. BACIP

52 analysis showed a significant impact of clear-felling with a 95% reduction in mean G. maculosus catches after a

53 clear-felling event where none of the individuals marked prior to felling were recaptured compared to 21%

54 recapture rates at the control site. Greater tree circumference in mature conifer stands correlated with greater

55 catches.

56   **Conclusions** Guidelines are needed to ensure the protection of Geomalacus maculosus in commercial forestry.

57   Interventions could include patch retention at final felling and/or translocation of the protected species.

58

60 **1 Introduction**

61 The Kerry Slug (Geomalacus maculosus Allman, 1943) has a disjunct distribution and is referred to as a

62 Lusitanian species in that it is restricted solely to western Ireland and north-western Iberia (Scharff, 1983; Patrão

63 et al. 2015). The species is protected under the European Union Habitats Directive (92/43/EC) and the Wildlife

64 Act in Ireland. As its status is listed as "inadequate" but improving in Spain, and there are no current

65 assessments available for Portuguese populations (EIONET 2014), Irish populations of the species are

66 considered to be of international importance. In Ireland, G. maculosus was originally considered to be

67 associated with deciduous woodland and peatlands (such as blanket bog and unimproved oligotrophic open

68 moor) in the south-west of the country (Anon 2010) where it is known to take refuge in rock crevices, soil or

69 bark (Platts and Speight 1998). Consequently, these habitats have been the focus of conservation efforts for the

70 species (Anon 2010). However, in recent years Kearney (2010) discovered the species breeding in a commercial

71 conifer plantation in Oughterard (Co. Galway) 200km north of its previously known distribution. Since then it

72 has also been found in numerous conifer plantations in the south-west of Ireland (Mc Donnell and Gormally

73 2011). Although there is no empirical evidence to date regarding how G. maculosus became established in

74 commercial conifer plantations, it is possible that as planted trees in the south-west of Ireland matured, they

75 were colonised by the slug from surrounding peatlands in which the species was naturally present. It has also

76 been hypothesised by Reich et al. (2012) that the population in Oughterard was introduced by forestry

77 machinery. Although G. maculosus is known to eat lichens and mosses on blanket bogs, it also eats lichens,

78 mosses and liverworts commonly found growing on the trunks of mature conifers in commercial plantations

79 (Reich et al. 2012). While little is known regarding the use by G. maculosus of microhabitats within the tree

80 canopy, it is likely that the species occurs in the upper reaches of mature conifer trees where lichens also

81 proliferate. Geomalacus maculosus is rarely seen or trapped on the ground between trees (Johnston et al. 2016)

82 but it is found beneath mosses at the base of mature conifers in unsuitable weather conditions during which time

83 the species is generally absent from the portion of tree trunks visible from ground level (pers. obs.).

84 Some studies indicate that biodiversity can be enhanced by forest plantations but this is more likely to happen

85 when native tree species are planted and forest plantations do not supplant natural ecosystems (Bremer &

86 Farley, 2010; Carnus et al., 2006). In addition, practices such as clear-felling, the norm for harvesting

87 commercial conifer plantation stands in Ireland, results in a rapid transformation of a forested landscape into an

88 open one. It can impact forest fauna with the process of harvesting itself causing considerable disturbance to

89 ecosystems and changes to the physical environment (Larsen 1995). The low mobility of slugs (Strayer et al.

90 1986) and their susceptibility to dehydration (Prior 1985) mean that changes in microclimate can also have an

91 adverse effect on populations in disturbed areas. In addition, slug assemblages have been found to be sensitive

92 to forestry management (Nystrand and Granström 2000; Kappes 2006; Rancka et al. 2015). In particular, Strayer

93 et al. (1986) suggest that disturbances (through forest fires, clear-felling or agricultural cropping) in New

94 England forests could reduce gastropod densities with some species becoming extinct at a local scale as a result.

95 However, they also suggest that recovery of gastropods post disturbance is rapid. Nevertheless, Platts and

96 Speight (1988) noted that forestry operations in Portugal appear to have eradicated G. maculosus from sites in

97 which it was previously found although no time scale is given in this regard. For these reasons, the presence of

98 this protected species in commercial conifer plantations in Ireland is of concern. Listed among current threats to

99 the species are forest planting on open ground, forest replanting and forestry clearance (NPWS 2013).

100 Nevertheless, the National Parks and Wildlife Service (NPWS), in its 2013 Article 17 report to the EU on the

101 conservation status of Irish species and habitats, states that G. maculosus is "resilient" to clear-felling despite its

102 short-term negative impact (NPWS 2013). However, this statement, primarily based on preliminary studies (Mc

103 Donnell and Gormally 2011; Reich et al. 2012), is qualified by the recommendation that more data are required

104 regarding the temporal occupation of woodland by the species in addition to its responses to forestry operations

105 (NPWS 2013). The absence of comprehensive population estimates for G. maculosus is also highlighted (NPWS

106 2013).

107 Only one study, to date, has investigated G. maculosus population sizes in clear-fell and mature conifer stands

108 (Reich et al. 2017). The study, undertaken in a single plantation, recorded significantly lower catches of G.

109 maculosus in a clear-felled stand (felled five years prior to the study) than in mature plantations. Since no data

110 regarding G. maculosus catches prior to felling were available for the study, Reich et al. (2017) recommended

111 that a before-after-control-impact assessment of the species be undertaken in future investigations given forestry

112 manager obligations to protect G. maculosus. This is particularly urgent since current forestry guidelines for

113 commercial forests in Ireland (published prior to the discovery of G. maculosus in commercial conifer

114 plantations) do not list the potential impact of forestry practices on the species (Forest Service 2009).

115 In the Republic of Ireland, Coillte - The Irish Forestry Board Limited (a commercial company with the

116 government as a shareholder) owns approximately 54% of the national forest estate (DAFM 2016). It currently

117 holds Forest Stewardship Council (FSC) certification which requires that its forests be managed with

118 consideration for ecosystems and biodiversity (Principle 6, FSC 2016). Given the current gaps in the knowledge

119 and Ireland's obligations under the EU Habitats Directive coupled with the commitment of Coillte to FSC

120 certification, further study is urgently required. To address these gaps, this study aims to:

121 1. Compare G. maculosus captures across mature, exotic Sitka spruce dominated plantations, previously clear-

122 felled stands and adjacent peatland habitats

123 2. Determine the suitability, for forest managers, of population estimate models for G. maculosus

124 3. Assess the implications of felling by comparing relative abundances of G. maculosus directly before and after

125 the clear-felling of a mature, exotic Sitka spruce dominated plantation.

126

127 **2 Materials and Methods**

128 2.1 Study areas

129 Four study sites (1-4) consisting of commercial Coillte-owned forestry plantations and adjacent peatland areas

130 within the distribution range of G. maculosus in the south-west of Ireland were chosen in 2014. The study sites

131 (12 – 40km apart) were those where clear-felling of at least one stand of mature plantation was scheduled to take

132 place within the lifetime of the project and where G. maculosus was known to be present.

133 Ten mature (predominantly Picea sitchensis) plantation stands distributed among four sites (2-3 stands per site)

134 were selected (Table 1). The stands (hereafter referred to as MP) were planted by Coillte on peatland in the early

135 1970s (Coillte, 2014) and were of felling age at the start of this study. Originally two stands (a & b) were

136 selected with stand "a" acting as control and stand "b" scheduled for felling within the lifetime of the project

137 (July 2014 to October 2015). However, due to changes in the felling schedule caused by Storm Darwin

138 (February 2014), the impact assessment using Before-After–Control-Impact-Paired (BACIP) analysis was

139 limited to just one of the four planned MP stands scheduled for felling (i.e. stand 2b). Two additional stands (2c

140 and 3c) were included in the study as back-ups in the event of further changes to the felling schedules. However,

141 none of the remaining or additional sites were felled in sufficient time to allow a before and after comparison.

142 Therefore, the data from stands 2c and 3c were subsequently incorporated in the MP dataset (total number of

143 MP stands = 10). Four previously clear-felled stands (hereafter referred to as PCF) (1 stand per site) were also

144 selected. These had been felled in 2013 prior to the start of the project and at the time of the study were

145 dominated by P. sitchensis tree stumps interspersed with, inter alia, Digitalis purpurea L., Juncus effusus L. and

146 mosses. Four adjacent areas of peatland (hereafter referred to as PL) (1 adjacent peatland per site) were also

147 selected. Vegetation in the peatlands was dominated by Molinia caerulea (L.) Moench and Calluna vulgaris (L.)

148 Hull.

149 2.2 Sampling design

150 Two sampling methods (details given below) were utilised in this study, namely sampling using refuge traps

151 (July 2014 - November 2015) and searching by hand (June – September 2015). For the trapping method, a

152 sample of nine trees (3x3), at least 10m from the edge of the forest was selected in each mature forest stand.

153 Mature forest stands were situated a minimum of 200m from each other to prevent any potential cross over of

154 populations within the compartments. A single refuge trap (De Sangosse, Pont du Casse, France, hereafter

155 referred to as "trap") was fixed to the north side of each tree (using nails and string) at 1.5m above ground level

156 after Mc Donnell and Gormally (2011). The traps consist of three layers: a perforated plastic layer, a padded

157 fabric layer to retain moisture, and a metallic foil outer layer (Johnston et al. 2016). Refuge traps which

158 measured 0.5 x 0.5m permitted the calculation of numbers of catches per m^2. While Johnston et al. (2016)

159 demonstrated that traps placed near the base of trees result in fewer catches than traps placed on trees at 1.5m

160 above ground level, it was not possible (for reasons of health and safety in combination with time constraints) to

161 place traps further up the trees. In clear-fell stands, individual traps (secured using nails and string) were placed

162 on the north side and top of nine (3x3) tree stumps (18 - 27cm high) situated at least 10m from the stand edge.

163 At peatland sites, nine traps were placed on rocks using methods described by Mc Donnell and Gormally (2011)

164 for G. maculosus sampling on rock outcrops in peatland. In addition, in each habitat (at a minimum distance of

165 45m from the tree, stump or rock traps), nine (3x3) traps (1.5m apart) were secured (using tent pegs) over

166 vegetation/bare soil on the ground between trees, tree stumps and rocks. These traps (hereafter referred to as

167 "ground traps") were deployed because Mc Donnell and Gormally (2011) showed that G. maculosus can move

168 between trees and along the forest floor. While protocols using traps follow those of Mc Donnell and Gormally

169 (2011), additional sampling methods (i.e. hand searching, described in section 2.4) were undertaken over four

170 months (June to September 2015) to allow for any possible variation in trapping efficiency across habitats.

171 Shortly before the tree felling event took place at site 2b during the course of this study, traps were removed for

172 health and safety reasons. These traps were then replaced on the remaining stumps, in the newly clear-felled

173 stands (hereafter referred to as NCF) following the removal of logs from the site.

174 2.3 Mark-recapture studies

175   Once a month (over a 16-month period), slugs were marked every day (hereafter referred to as sampling days)

176   over five consecutive days (hereafter referred to as sampling weeks) based on recommendations by Reich et al.

177   (2015, 2017) and Kendall & Bjorkland (2001) to ensure a robust design. This decreases bias and allows for a

178   more efficient estimate of population dynamics. On each of the sampling days, all of the traps were checked at

179   every site and in every habitat. For the purposes of this study, slugs greater than 1cm in diameter when rolled

180   into a defensive ball are referred to as "adults" (based on the size categories from Reich et al., 2015) and hence

181   large enough to be tagged. Smaller slugs (too small to tag effectively) were considered sub-adults and are

182   hereafter referred to as "juveniles". Confirmation by dissection to determine sexual maturity was not an option

183   in this live population study. In addition, weight could not be used as an effective determinant of maturity in the

184   field since humidity levels are known to affect the weight of slugs (A O'Hanlon, pers. comm.).

185   The marking strategy for this project was based on that developed by Mc Donnell and Gormally (2011). Visible

186   Implant Elastomer (VIE) (Northwest Marine Technology, Shaw Island, Washington) in nine different colours

187   was used to mark adult slugs. VIE is a medical-grade, silicone based material which is injected as a liquid and

188   cures into a pliable, biocompatible solid (Northwest Marine 2015). Marks for the different months were

189   distinguished from each other based on different colours and locations of tags. For the initial nine months, from

190   July 2014 to March 2015, tags were inserted into the left hand side of the foot from the head down to the tail.

191   For the final seven months, from April to October 2015, the tags were placed into the right hand side of the foot

192   from the tail to the head. The colour location was reversed for slugs caught in ground traps to distinguish them

193   from those caught in tree traps. To check for the presence of tags in captured individuals, each slug was lightly

194   pressed against a clear piece of plastic and a torch emitting a Deep purple light (405 nm) (Northwest Marine

195   Technology, Shaw Island, Washington), was then shone over the individual. The torch is designed to cause red,

196   orange, blue, yellow, green, and pink VIE to fluoresce, making tags easier to observe, particularly in poor light

197   conditions. The remaining three colours which were used i.e. brown, black and purple do not fluoresce. Every

198   adult G. maculosus found was checked for any previous tags, recorded and marked with the relevant colour for

199   the sampling month. Any juvenile slugs caught were also recorded to provide information on juvenile activity

200   levels but juveniles were not tagged due to their small size. Slugs were then returned to the relevant trap.

201   Damaged traps were replaced as required.

202   2.4 Hand searching

203   Johnston et al. (2016) found that hand searching was more effective than traps in clear-fell stands particularly

204   after rain when slugs emerged and became active. Traps also tended to dry out in open clear-fell stands thereby

205   rendering them less attractive to slugs unlike traps under the shade of trees in mature plantations. For this reason

206   hand searches were undertaken for a limited period (June and September 2015) at mature forest / clear-fell

207   stands and peatland areas at a distance of 45m from all other trapping locations. Hand searches were completed

208   on nine trees in mature forest stands, nine stumps in the clear-fell stands and over a marked area of similar size

209   (5m x 5m) in peatland. Hand searches for both adult and juvenile G. maculosus were undertaken by two people

210   for five minutes per person in each of the designated areas, giving a total of ten minutes searching for each

211   sampling day. Searches consisted of examining tree trunks (to a maximum height of approximately 2m), tree

212   stumps and rocks in addition to examining the areas in between these features, thereby surveying all likely

213   refuges in each habitat. Where G. maculosus was found during hand searching the individuals were not tagged.

214   Tree circumference at breast height (1.5m) and at the base of trees was recorded using a flexible tape measure.

215   Percentage cover of moss from ground level to 1.5m on tree trunks was also recorded. Data regarding MP

216   management such as year of planting were provided by Coillte (2014) (Table 1).

217   2.5 Data analysis

218   All analyses were undertaken using SPSS version 21 except for population estimates (Jolly-Seber and Schnabel

219   models) which were calculated using Excel through formulae described by Krebs (1999) and Greenwood

220   (1996). The Jolly-Seber model allows for an "open" population where the number of animals varies (due to

221   immigration, emigration, birth and death) while the Schnabel model is based on the assumption of a "closed"

222   population which assumes that the number of animals at the site does not vary during the period of study (Krebs,

223   1999). In the comparisons of habitats and direct comparisons between control and impact stands, where

224   assumptions of normality and homogeneity of variance were violated, Welch's t-test or Welch's ANOVA was

225   used followed by a Games-Howell post hoc test to determine pair-wise differences where more than two groups

226   were examined. Correlations were determined using Spearman's rank correlation. The Before-After-Control-

227   Impact-Paired (BACIP) analysis (Smith 2002) was carried out using an Independent samples t-test on the

228   differences between control and impact sites before and after the impact (i.e. clear-felling).

229   3 Results

230   3.1 Comparison of G. maculosus catches in mature plantation (MP) stands, previously clear-felled (PCF) stands

231   and adjacent peatland (PL)

232   Catches are reported as mean catch number per sampling day for all MPs, all PCFs and all PLs to allow for

233   comparison across the different habitat types over the 16 months of sampling (Table 2). The stand subjected to a

234   clear-felling event during the course of this study (Site 2b) was not included in these analyses. The mean

235   number of adult G. maculosus catches per sampling day using traps was greatest in MPs (5.23), followed by PLs

236   (0.50) and PCFs (0.47). Significant differences were found between MPs and PCFs and between MPs and PLs

237   (P < 0.001 and P < 0.001 respectively, Welch's ANOVA followed by Games-Howell post-hoc analysis). The

238   mean number of juvenile catches, while considerably lower than those for adults, was also greatest in MPs

239   (0.47), followed by PLs (0.24) and PCFs (0.047). Significant differences were found between all three habitats

240   (Table 2).

241   Both with and without the addition of hand search data, the mean number of adult G. maculosus caught (June –

242   September 2015) was still greatest in mature forest stands, followed by PCFs and PLs with significant

243   differences between MPs and PCF/PL (Table 3). However, numbers of adult specimens found in PCFs when

244   hand searching was included was 3.8 times greater than where hand searching was not employed with a

245   significant difference found between the two sampling strategies (P < 0.001, Welch's T-test). The mean number

246   of juveniles was also greatest in the MPs but there was an 18 fold increase in the mean number of juvenile

247   specimens found in the PCFs when hand searching data were included (Table 3) with a significant difference

248   found between the data including and excluding hand searches (P = 0.015, Welch's T-test). No significant

249   difference, however, was found between data including and excluding hand searches for the MPs and PLs for

250   both adults (P = 0.766, P = 0.890 respectively, Mann-Whitney U-test) and juveniles (P = 0.881, P = 0. 953

251   respectively, Mann-Whitney U-test).

252

253   3.2 Population density estimates

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

255   recaptures (estimates are only considered to be accurate when the number of recaptured animals over the

256   sampling week is greater than ten (Greenwood 1996)). Within the MPs, estimates using the Jolly-Seber method

257   could only be calculated for six sampling weeks (out of a total possible 98) due to either low recaptures (less

258   than ten) or a failure of the Jolly-Seber goodness of fit test (Sutherland 1996). Of these six estimates, only those

259   at two MP stands, 2a and 3c (density of 0.7 individuals/m^2 and 1 individuals/m^2 respectively), could be

260   calculated during April 2015 when the overall goodness of fit was satisfactory. As with the Jolly-Seber method

261   population size estimates using the Schnabel method could not be calculated for PCF and PL habitats due to low

262   capture numbers. However, the Schnabel model was found to be a good fit in MPs for 33 out of 135 sampling

263   weeks. Estimates could not, however, be calculated for two of the MP stands (2c and 4b) due to low capture

264   numbers (Fig. 1). For the same reasons estimates could not be calculated in July 2014, January 2015, June 2015

265   or September 2015 for the remaining eight stands (Fig. 2). Mean (±SE) Schnabel population density estimates

266   in the mature plantations ranged from 9.61 (± 3.3) individuals/ m^2 to 23.49 (± 12.2) individuals/ m^2 with mean

267   number of individuals captured (excluding recaptures) over the sampling week and mean total catch per

268   sampling day following similar patterns (Fig. 1). Discounting occasions where estimates could not be calculated,

269   the mean (± SE) Schnabel population density estimate per m^2 in each month (Fig. 2) ranged from 24.4

270   individuals/ m^2 (± 6.4) in August 2014 (week 2) to 4.5 individuals/ m^2 (± 0) in February 2015 (week 8).

271   Significant positive Spearman's rank correlations were found in MPs between Schnabel population density

272   estimates and mean total catch of G. maculosus per sampling day (P < 0.004, r_s = 0.490) (Fig. 3a) and between

273   Schnabel population density estimates and numbers of captures (excluding recaptures) during sampling weeks

274   (P < 0.001, r_s = 0.891) (Fig. 3b). When captures for each of the sampling days (1 to 5) were averaged for the

275   MPs over the length of the study, the mean percentage of marked individuals in each catch increased over time

276   so that by day five a mean of 60% of captures consisted of marked individuals (Appendix 1). Overall, the

277   average percentage (± SE) of unmarked individuals was 25% (± 1%) of the catch in MPs, 59% (± 2%) in PCFs,

278   and 54% (± 1%) in PLs.

279   3.3 Before-After-Control-Impact-Paired (BACIP) assessment

280   As population estimates could not be calculated in NCF due to low numbers, BACIP analysis was carried out

281   using total catches per sampling day to allow for comparison post-impact (i.e. after a clear-felling event). Mean

282   number of individuals per sampling day (± SE) caught over two sampling weeks (i.e. ten sampling days) before

283   felling in the control and impact stands (2a and 2b respectively) were 6.9 (± 2.7) and 6.3 (± 1.3) respectively. No

284   significant difference was found between the control and impact stands prior to felling (P = 0.848, Welch's t-

285   test). Felling and forwarding was undertaken over five months (Fig. 4) during which time, for health and safety

286   reasons, no sampling took place. The traps were replaced in February 2015 onto the remaining stumps of the

287   trees which were sampled prior to the clear-felling event and two weeks later the first catches (post clear-felling)

288   were recorded. The mean number of individuals per sampling day (± SE) over the eight months following trap

289   replacement in the impact stand was 0.3 (± 0.1) while the corresponding months in the control stand had a mean

290   (± SE) of 6.2 (± 0.8) with a significant difference found between the two stands (P < 0.001, Welch's t-test).

291   None of the individuals captured over two sampling weeks in the impact stand prior to felling were recaptured

292   during eight sampling weeks post-felling in contrast to a 21% recapture rate at the control stand over the same

293   timeframe. The other three MP stands sampled (1a, 4a, 4b) during the same period yielded a mean recapture rate

294   of 38% (± 5.4% SE). In addition, in post impact sampling weeks, numbers were consistently lower in the impact

295   stand than those in the control stand, even when 10 minute hand searches were included (Fig. 4). A BACIP

296   analysis (Smith 2002) confirmed a significant impact from the felling event using data from trap catches only, as

297   well as when data from trap and hand searching catches were combined (P = 0.015 and P = 0.014 respectively,

298   Independent Samples t-test).

299   3.4 Stand characteristics

300   Across nine MPs, significant, moderate, positive Spearman's rank correlations were found between average

301   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

302   well as circumference at breast height (P = 0.015, r_s = 0.286; N = 81). No significant correlation was found

303   between average catch of adult G. maculosus per tree and the percentage moss cover (P = -0.58, r_s = 0.626; N =

304   81).

305   **4 Discussion**

306   4.1 Comparison of G. maculosus catches in mature plantation stand, previously clear-felled stands and adjacent

307   peatland.

308   Given that the adjacent peatland has been considered historically as a natural habitat for G. maculosus (Platts

309   and Speight 1988), it is surprising to find greater catches in mature plantation and previously clear-felled stands.

310   While these results are likely to reflect actual numbers found within the stands, it is important to consider

311   trapping efficacy across the three habitat types. Johnston et al. (2016) found that the area under traps on tree

312   stumps in previously clear-felled stands tends to be drier in comparison to those in mature plantations and the

313   adjacent peatland. The shape of tree stumps means that it is not possible to attach traps as tightly to the stump

314   surface and sides as it is on the tree trunks and rocks found in mature plantations and the adjacent peatland

315   respectively. It is likely that runoff from rainfall in mature plantations and the adjacent peatland enters the

316   narrow space between the trap and the surface to which it is attached thereby maintaining damp conditions

317   under the traps. In mature plantations tree shading will further delay drying of the traps. Clearly, drier traps

318   would be less attractive to slugs seeking to avoid dehydration and the greater numbers of slugs captured in the

319   previously clear-felled stands by hand collecting in combination with traps versus traps alone supports this

320   hypothesis. These findings emphasise the importance of undertaking hand searching in addition to traps,

321   particularly in clear-felled areas, when assessing sites for G. maculosus as suggested by Johnston et al. (2016).

322   Given the consistently greater numbers of G. maculosus found in mature plantations, conservation efforts should

323   focus more on commercial forestry to ensure adequate future protection of the species. Although Johnston et al.

324   (2016) hypothesised that G. maculosus moves up the tree to forage, no study has, to date, examined the

325   distribution of the species higher in the canopy. It is, therefore, still unknown how much of the tree and

326   associated microhabitats is used by the species. The impact of this on trapping efficiency and density estimates,

327   while outside the scope of this study, requires further investigation.

328   4.2 Population density estimates

329   Krebs (1999) describes the Jolly-Seber model as a method of population estimation for open populations, which

330   allows for births, deaths, immigration and emigration. As the Jolly-Seber method is generally unreliable without

331   at least ten recaptures (Greenwood 1996), its use was limited in this study because many sampling occasions,

332   particularly those in previously clear-felled stands, newly clear-felled stands and peatland habitats, had to be

333   eliminated due to a failure to meet this requirement. In addition, the method requires that there is some

334   permanent emigration (Sutherland 1996) but high recapture rates in mature plantation stands (when taken over

335   the entire length of the study) could indicate a degree of "trap-happiness" thereby violating this assumption. The

336   continual recapturing of individuals over several succeeding months in the mature plantations suggests that the

337   dispersal rate of the individuals was relatively low, likely due to movement predominantly occurring up and

338   down the tree as opposed to between trees. Lack of movement between trees, at least at ground level, is

339   supported by low numbers of catches found under traps placed on the forest floor (Johnston et al. 2016).

340   While the Schnabel population estimate assumes that a population size is constant (Alcoy 2013), the advantage

341   of using this estimate is that the low level of dispersal of individuals in the population fits closest to this model.

342   However, it was still not possible to obtain population estimates in previously clear-felled stands, newly clear-

343   felled stands and peatland habitat. This was because there were either no recaptures to calculate the estimate or

344   the Schnabel goodness of fit test was violated. The Schnabel estimates in the mature plantations, however,

345   correlate with both the mean total catch per sampling day and the number of captures (excluding recaptures)

346   over the sampling week. This indicates that despite the limitations of the method, the estimates reflected the

347   actual numbers of individuals caught during sampling. Activity in terrestrial gastropods is associated with a

348   number of environmental factors (Young and Port 1989), and (apart from July 2014 at the start of the study)

349   greater proportions of unmarked G. maculosus individuals were present in the warmer months from April to

350   August than in colder months which is reflected in Johnston et al. (2016) who found greatest catches in summer

351   and autumn months. When the proportion of unmarked individuals was averaged over sampling days, 60% of

352   the catch on the last sampling day (day 5) consisted of recaptured individuals entering the traps. It is likely that

353   individuals that were previously deemed too small to tag may have entered the appropriate size class in later

354   months, which may have contributed to the percentage of unmarked individuals. Nevertheless, the majority of

355   individuals were cptured over five consecutive sampling days in mature plantation stands. The Schnabel

356   population size estimates calculated also correlate with the mean total catch per day of G. maculosus adults.

357   Since, calculating population size estimates using mark-recapture is labour intensive and requires specialist

358   training and equipment, it is unlikely that this will be adopted by foresters in conservation strategies for the

359   species. However, the use of mean total catch per day as a proxy for foresters undertaking surveys to estimate

360   population sizes of G. maculosus in mature conifer plantations, at least in the south-west of Ireland, may provide

361   a more feasible solution.

362   4.3 Before-After-Control-Impact- Paired (BACIP) assessment

363   It is important to note that, due to the re-scheduling of felling operations as a result of Storm Darwin (February

364   2014), only one of the original four selected stands of mature conifers was felled with sufficient time to allow

365   sampling before and after the impact event. While it would be inadvisable to make generalisations on the basis

366   of a single felling event, the results are discussed given that this is the first ever BACIP assessment for G.

367   maculosus and the results can be used to inform the design of future replicated trials. Mean catch per sampling

368   day post-felling at the impact stand dropped by 95% compared to only a 10% drop in the control stand. These

369   results reflect the findings of Strayer et al. (1986) who reported that disturbances (including clear-felling) may

370   reduce densities of gastropods. Individuals tagged prior to felling were not present post-felling at the impact site

371   unlike the control site where 21% of tagged slugs were subsequently recaptured. While it is possible that those

372   few individuals found within the impact stands post-felling had colonized from nearby habitats, the effect of

373 surrounding stands harbouring G. maculosus on the colonisation of clear-felled stands requires further

374 investigation particularly given the low dispersal ability of G. maculosus within habitats (McDonnell and

375 Gormally 2011).

376 4.4 Influence of stand characteristics

377 Significant, moderate, positive correlations were found between the average catch of adult G. maculosus per tree

378 in the mature plantation stands and circumference at both the base of the tree and at breast height. This

379 correlation mirrors that found by Reich et al. (2012) who hypothesised that this was due to the association of

380 greater bryophyte cover on older trees with larger circumference at breast height. However, unlike Reich et al.

381 (2012), species catch across a range of mature plantation stands did not correlate with percentage moss cover.

382 As terrestrial gastropods are known to avoid exposure to unfavourable conditions (Rollo 1982) and evade cold

383 temperatures by moving below ground (Cook 2004), it is likely that G. maculosus makes use of the base of the

384 tree as a refuge during non-optimal weather conditions. Indeed, the authors have observed G. maculosus

385 sheltering at the base of trees throughout the study period. This suggests that while G. maculosus makes use of

386 bryophytes as a source of both food and shelter (Platts and Speight 1988), the association with larger tree

387 circumference, particularly at the base of the tree, may be of greater importance for the species as a larger

388 circumference would allow for a greater number of slugs to shelter.

389 4.5 Conclusions

390 Of the three habitats investigated in this study the greatest number of G. maculosus captures occurred in mature

391 plantations, highlighting the need for the protection of the species where they occur in commercial forestry. In

392 addition, the greater catches of G. maculosus associated with higher quality forest stands in commercial forestry

393 is not compatible with current forestry practices in Ireland where clear-felling and removal of such stands is the

394 norm. BACIP analysis, albeit at a single location, shows a significant impact of clear-felling on G. maculosus

395 captures with a 95% reduction in catches post-felling. Further replicated trials are required to determine whether

396 this accurately reflects the impacts of clear-felling at other forests where G. maculosus is found. In addition,

397 studies examining longer term impacts are needed followed by an examination of impacts during the forest

398 cycle i.e. replanting, fertiliser / herbicide use and thinning. Current legislation under the Habitats Directive

399 requires Member States to prohibit, among other factors, the "deterioration or destruction of breeding sites or

400 resting places" of an animal species listed in Annex IV in their natural range, of which G. maculosus is one (EC

401 2007), and under Irish legislation the species is protected wherever it occurs. The results of this study, when

402 taken into account in the context of these legislative obligations, indicate the need for practical mitigation

403 measures. Two possible measures include retention of small stands of forestry (Raivio et al. 2001) and

404 translocation of species (Germano et al. 2015). While a short-term study undertaken in Co. Galway by Reich et

405 al. (2012) demonstrates the possible benefits of retaining 3m stumps post-clear-felling, the long-term benefits to

406 G. maculosus have not yet been assessed. In addition, translocation has never been examined in G. maculosus

407 and therefore it is not possible to speculate on this as a measure without further research into both the carrying

408 capacity of forests and the ability of G. maculosus to acclimatise to new areas. Given these findings, further

409 research is urgently required to determine practical mitigation measures to protect the species where it occurs in

410 commercial forestry.

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495   **Tables**

496   **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

497   [1]Source: Coillte 2014; a, b and c refer to stands designated as controls (a); stands designated for felling during
498   the study (b); and additional stands as "back-ups" in the event of unpredicted changes to felling schedules (c).

499   [2] Coillte stands are on average 19ha in size (Coillte, 2014)

500   [3] The sole forest stand which was subjected to a clear-felling event during the course of this study
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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 clearfelling event during the course of the study are not included in this table. [2] Individuals > 1cm (diam.) when rolled into a defensive ball. [3] Individuals < 1cm (diam.) when rolled into a defensive ball.

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527 **Table 3** Comparison of G. maculosus catches across nine mature plantation stands (MP), four previously
528 clearfelled forest stands (PCF) and four adjacent peatlands (PL) using traps only (**Tr**) and traps in combination
529 with hand searching (**Tr&Hs**) (June – September 2015) with traps placed on tree trunks, stumps and rocks
530 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 ($\pm$ SE)[2]	3.68 ($\pm$ 0.4)	3.93($\pm$ 0.37)	0.56 ($\pm$ 0.1)	2.13 ($\pm$ 0.4)	0.53 ($\pm$ 0.09)	0.58 ($\pm$ 0.10)
P values						
MP	-	-	-	-	-	-
PCF	**0.000**	**0.001**	-	-	-	-
PL	**0.000**	**0.000**	0.960	**0.000**	-	-
Mean no. of juveniles ($\pm$ SE)[3]	0.71 ($\pm$ 1.22)	0.73 ($\pm$ 1.24)	0.02 ($\pm$ 0.02)	0.36 ($\pm$ 0.15)	0.16 ($\pm$ 0.05)	0.21 ($\pm$ 0.06)
P values						
MP	-	-	-	-	-	-
PCF	**0.000**	**0.115**	-	-	-	-
PL	**0.000**	**0.000**	**0.026**	0.614	-	-

531 **Adult:** Test statistic Tr = 38.7, Test statistic Tr&Hs = 44.5; df = 2; P < 0.001, Welch's ANOVA. P values given
532 in bold indicate significant differences between habitats, Games-Howell multiple comparison test; **Juvenile:**
533 Test statistic Tr = 23. 9, Test statistic Tr&Hs = 8.7; df = 2; P = < 0.001, Welch's ANOVA. P values given in
534 bold indicate significant differences between habitats, Games-Howell multiple comparison test.
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536 [1]Data from Site 2b which was subjected to a clearfelling event during the course of the study are not included in
537 this table. [2]Individuals > 1cm (diam.) when rolled into a defensive ball. [3] Individuals < 1cm (diam.) when rolled
538 into a defensive ball.

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540 **Captions of figures**

541 **Fig 1.** Mean[1] (± SE) G. maculosus per m^2 in mature plantation (MP) stands over a period of sixteen months

542 (July 2014 – October 2015)[2]: (i) Mean Schnabel population estimates; (ii) Mean number of individuals captured

543 (excluding recaptures) over sampling week; (iii) Mean of average total catch per day.

544 [1] Means are calculated on the basis of the number of sampling months in which Schnabel population estimates

545 could be calculated (i.e. N)

546 [2]Schnabel population estimates for compartments 2c and 4b could not be calculated due to low capture numbers

547 and lack of fit.

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549 **Fig 2** Mean[1] (± SE) G. maculosus per m^2 in mature plantation (MP) stands for each month from July 2014 to

550 October 2015: (i) Mean Schnabel population estimates[2]; (ii) Mean number of individuals captured (excluding

551 recaptures) over sampling week; (iii) Mean of average total catch per day.

552 [1] Means are calculated on the basis of the number of MP stands in which Schnabel population estimates could be

553 calculated (i.e. N)

554 [2]Population estimates for July (2014) and January / June / September (2015) could not be calculated due to low

555 capture numbers and violation of the goodness of fit.

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557 **Fig. 3** Relationship between Schnabel population estimates (July 2014 - October 2015) and: (a) mean total catch

558 of G. maculosus per sampling day in eight mature plantations (MP; N=33); (b) G. maculosus captures

559 (excluding recaptures) per sampling month in eight mature plantations (MP; N=33).

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561 **Fig 4** Mean (± SE) number of catches of adult G. maculosus per sampling day in the control and impact stands

562 over 15 months between July 2014 and September 2015. Traps were removed from the impact site during

563 felling for health and safety reasons. *Months where hand searching data were included.

564 **Appendix 1** Mean percentage of total catch of G. maculosus per sampling day (N=117) consisting of

565 individuals recaptured at least once during the sampling week in mature plantations (MP) (July 2014 - October

566 2015)

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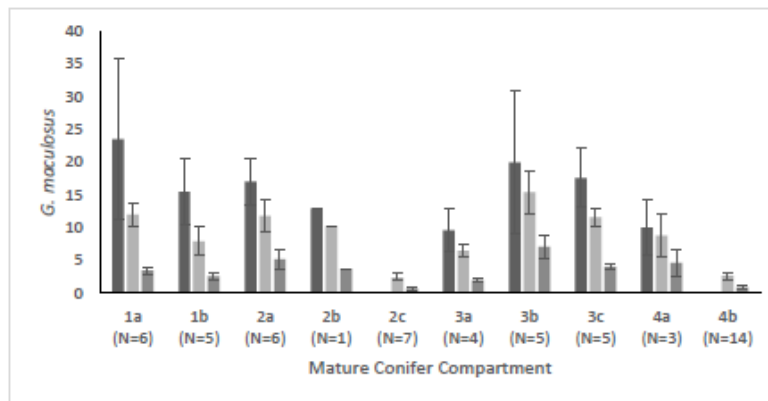
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Fig 1. Mean (± SE) G. maculosus in mature plantations (MP) over a period of sixteen months (July 2014 – October 2015): (i) Schnabel population estimate (mean number / m^2)[1]; (ii) number of individuals captured (excluding recaptures) over sampling week (mean / sampling week / m^2); (iii) total catch (mean / sampling day / m^2). N = number of months; error bars = SE.

[1]Population estimates for compartments 2c and 4b could not be calculated due to low capture numbers and lack of fit.
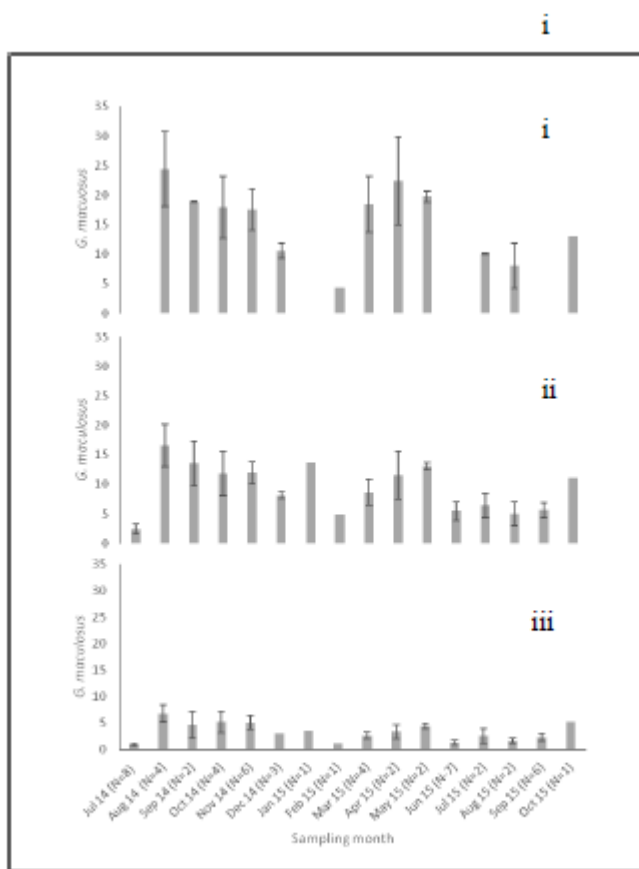
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Fig 2 Mean (± SE) number of G. maculosus individuals in mature plantations (MP) on each sampling month

(July 2014 – October 2015): (i) Schnabel population estimate (mean / m^2); (ii) number of individuals captured

(excluding recaptures) over sampling week (mean / m^2); (iii) total catch (mean per sampling day) / m^2. N =
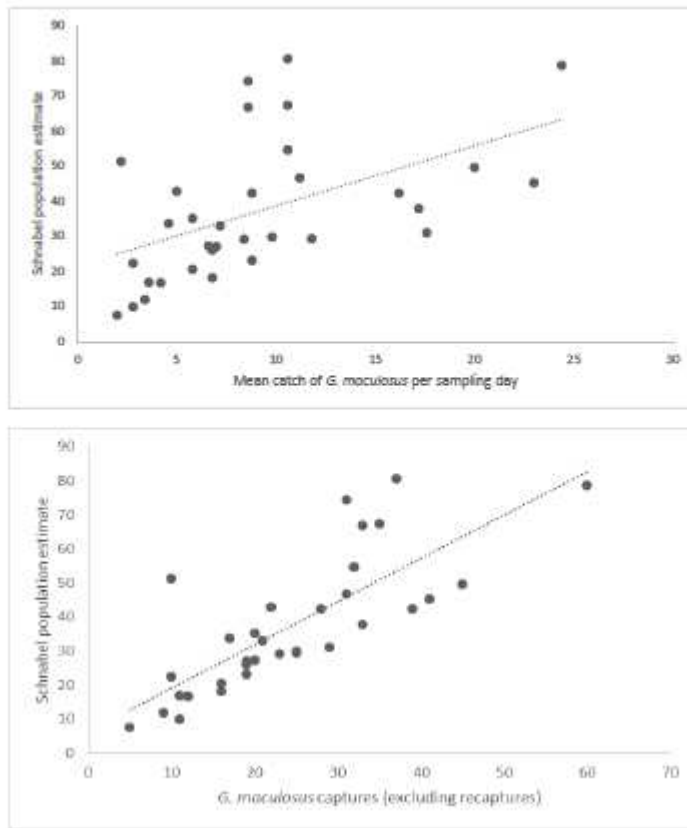
number of stands; error bars = SE.

[1]Population estimates for July 2014, January, June and September 2015 could not be calculated due to low

capture numbers and violation of the goodness of fit.

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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).

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619   **Fig 4** Mean (± SE) number of catches of adult G. maculosus per sampling day in the control and impact stands

620   over 15 months between July 2014 and September 2015. Traps were removed from the impact site during

621   felling for health and safety reasons. *Months where hand searching data were included.

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625   **Appendix 1** Mean percentage of total catch of G. maculosus per sampling day (N=117) consisting of

626   individuals recaptured at least once during the sampling week in mature plantations (MP) (July 2014 - October

627   2015)