1   **Negative impacts of felling in exotic spruce plantations on moth diversity mitigated by**

2   **remnants of deciduous tree cover**

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26   **Abstract:**

27   Moths are a vital ecosystem component and are currently undergoing extensive and severe declines

28   across multiple species, partly attributed to habitat alteration. Although most remaining forest cover

29   in Europe consists of intensively managed plantation woodlands, no studies have examined the

30   influence of management practices on moth communities within plantations. Here, we aimed to

31   determine: (1) how species richness, abundance, diversity of macro and micro moths in commercial

32   conifer plantations respond to management at multiple spatial scales; (2) what the impacts of forest

33   management practices on moth diversity are, and (3) how priority Biodiversity Action Plan (BAP)

34   species respond to management. BAP species were selected as they represent formerly widespread

35   and common species, which have undergone substantial declines in the UK and Europe. We assessed

36   moth communities in three conifer plantations in Northern England and Scotland by light trapping,

37   combining local (e.g. age of planting) and landscape level (e.g. proximity to felled areas)

38   characteristics to evaluate the impacts of forest management on moths. We found no relationship

39   between local factors and moth richness, abundance and diversity but the amount of clear felling in

40   the surrounding landscape had a strongly negative correlation. In contrast, the amount and

41   proximity of broadleaf cover in the surrounding landscape positively influenced macro moth richness

42   and abundance. For six BAP species, abundances were lower close to felled areas but increased with

43   the size of adjacent broadleaf patches. We conclude that clear felling negatively affects moths,

44   probably through alteration of habitats, the loss of larval host plants, and by limiting dispersal. A

45   shift to continuous cover and maintaining broadleaf tree cover within plantations will greatly

46   enhance their value for moth communities.

47   **Keywords: Moth; Lepidoptera; abundance; species richness; plantation management; landscape**

48   **heterogeneity**

49

50   **1. Introduction**

51   Maintaining and restoring biodiversity is a key tenet in sustainable ecosystem management, the

52   paradigm currently guiding habitat management practices across Europe and North America (Ober &

53   Hayes 2010). This is driven by concern about world-wide declines in species and populations across a

54   range of taxa (Dirzo et al. 2014) and recognition that much of this is driven by habitat loss and

55   fragmentation, caused by anthropogenic change (Thomas 2004). In many countries the timber

56   industry has responded to recognition of the importance of biodiversity by shifting focus from purely

57   timber production to one which encourages sustainable practices that promote both wildlife

58   conservation and sustainable timber yields (Macdonald et al. 2009). In Europe this has been driven

59   by policy change initiated as a result of the Convention of Biological Diversity, requiring explicit

60   consideration of environmental, economic and social objectives and a multi-purpose approach to

61   forestry (Watts et al. 2008). However, efforts to assess the impact of forest practices can be

62   challenging as there is often inadequate knowledge of the current distribution and abundance of

63   many taxa in managed forest systems (Ober & Hayes 2010).

64   Plantation forests are generally considered poor for biodiversity as they are primarily

65   composed of non-native tree species, often in monocultures, which are under an intensive

66   management regime (Brockerhoff et al. 2008). However, they usually constitute the largest patches

67   of tree cover in many European countries and as such may be valuable for preserving biodiversity if

68   managed sympathetically. One of the few studies carried out at a national scale demonstrated that

69   plantations can support diverse invertebrate communities in the UK, and that invertebrate

70   community composition and abundance is most affected by tree species planted and geographic

71   location (Humphrey et al. 2003). The structure of the plantation was also important for some

72   groups: ground dwelling Carabid diversity decreased with canopy cover whereas overall Coleopteran

73   richness and abundance in the canopy increased (Humphrey et al. 2003). The effect of stand age on

74   invertebrate communities can also vary between taxa. Higher abundance and diversity of Coleoptera

75   has been associated with older *Larix kaempferi* (Larch) and *Picea sitchensis* (Sitka Spruce) plantations

76   in Japan and Northern Ireland due to increased heterogeneity and regeneration of native trees

77   (Ohsawa 2005; Oxbrough et al. 2010). However, the high canopy cover in mature plantations can

78   negatively affect other groups associated with open habitats (e.g. Arachnid diversity; Oxbrough et al.

79   2010).

80   Despite being a speciose taxonomic group and an important component of the invertebrate

81   community, the impacts of plantation forestry on night active Lepidoptera are yet to be explored.

82   Substantial declines of many moth species have occurred in the last few decades; two thirds of

83   common and widespread species in the UK have suffered rapid population decreases (Conrad et al.

84   2006) with similar patterns occurring in Finland (Mattila et al. 2006) and Sweden (Franzén &

85   Johannesson 2007). Rapid economic development, urbanisation, changes to silvicultural

86   management and agricultural expansion have all been implicated in causing these declines (Conrad

87   et al. 2006; Fox et al. 2013). Taken together, these studies provide overwhelming evidence that

88   moths are facing declines on a large geographic scale, across a range of habitats, which mirrors

89   similar effects found in less species rich groups such as butterflies and bumblebees (Warren et al.

90   2001; Goulson et al. 2008). Such losses are likely to have substantial effects at both higher and lower

91   trophic levels. Moths are a key component of terrestrial ecosystems, providing ecosystem services

92   through modification of ecosystem functioning by saproxylic species (Merckx et al. 2012), impacting

93   upon plant growth through larval feeding activity, acting as pollinators and providing food for a

94   range of taxa such as birds, small mammals and bats (Fox et al. 2013).

95   Intensified silvicultural practices have been suggested as one major driver of the decline in

96   moth diversity and abundance (Fox et al. 2013). However, most studies have only focussed on the

97   negative effects that a reduction in traditional deciduous forest management practices has had on

98   lepidopteran species, and have not considered the role that non-native plantations may play.

99   Reductions in deciduous forest management techniques such as coppicing and opening up rides

100   have resulted in lower moth diversity by increasing structural complexity and changing botanical

101   communities (Fox et al. 2013; Merckx et al. 2012; Warren & Bourn 2011). In general, moths

102   associated with deciduous trees have declined throughout Europe, with larval host plant specificity a

103   key factor in extinction likelihood in parts of Scandinavia (Mattila et al. 2006; Franzén & Johannesson

104   2007), whilst species associated with conifer trees have increased (Fox et al. 2013). Our current

105   knowledge of moths in non-native coniferous plantations comes largely from studies which have

106   focused on the management of pest species, and to the best of our knowledge no research has

107   explicitly explored moth community composition and the impacts of forest management in exotic

108   plantations.

109   Whilst little is known about the impacts of timber harvesting on Lepidoptera in non-native

110   plantations, studies in native hardwood forests have suggested that effects are largely negative. In

111   Indiana and Ohio, Summerville and Crist (2002, 2014) demonstrated that clear felling in native

112   hardwood forests disrupted moth communities beyond the stand being felled, limiting the diversity

113   of species able to persist within the landscape. Impacts of timber harvest on Lepidoptera can persist

114   for up to 60 years (Summerville et al. 2009), although Summerville (2013) suggests that less

115   intensive practices such as shelterwood harvest (removal of 15% standing wood) may support a

116   higher richness and abundance of moth communities. In native conifer forests in Oregon, moth

117   dominance and diversity was associated with greater canopy cover whereas richness was only

118   affected by elevation, with higher species richness at lower elevations (Ober & Hayes 2010). These

119   studies from North America demonstrate that managed native forest systems can support diverse

120   lepidopteran communities, but the extent to which this is true in managed non-native plantations

121   has not yet been examined. Specifically, in this study we aim to assess the impact of the following on

122   moth abundance, richness, diversity and dominance in conifer plantations:

123   1.   Influential, local scale plantation characteristics (e.g. age of planting, ground cover);

124   2.   Proximity and prevalence of clear felling in the surrounding landscape;

125   3.   Proximity and prevalence and of broadleaf tree cover within the surrounding landscape.

126   Since declining moth species might respond differently to the wider moth community, we examined

127   the impacts of the above characteristics for moth communities as a whole, and separately for

128   priority biodiversity action plan (BAP) species. These are formerly widespread and common species

129   which have undergone population declines of between 70 – 90% in the last few decades, and as such

130   are of particular scientific interest (Fox et al. 2013).

131   **2. Methods**

132   The study was conducted in three plantation forests in Central and Southern Scotland and Northern

133   England (Figure 1). Widespread deforestation had already occurred in this area by the Holocene;

134   prior to the planting of the plantations in 1920 – 1940, the sampling areas would have consisted of

135   open, upland moorland predominantly used for sheep grazing, with small patches of remaining

136   broadleaf. The three forests were chosen for their large size (ranging from 30,000 ha in Cowal and

137   Trossachs to 60,000 ha in Kielder and 114,000 ha in Galloway), high productivity and the

138   predominance of *Picea sitchensis*, the most commonly planted and intensively managed coniferous

139   tree species in the UK, and a common plantation tree species in Europe (Boye & Dietz 2005). Within

140   each forest, multiple sites, a minimum of 4 km from each other, were selected using a Forestry

141   Commission sub-compartment database within a Geographic Information System (GIS) (ArcMap

142   10.1, ESRI) based on stand (a unit of plantation management) age and species composition (Figure

143   1).

144   In total, seven sites were surveyed in Cowal and Trossachs, 12 in Galloway Forest and 12 in

145   Kielder Forest. Where possible a stand of trees at each management stage was selected in each site,

146   which was a maximum of 2km^2 in size. Not all sites had all stands of each management age resulting

147   in an unbalanced design of between four and six stands per site and a total of 285 stands across 31

148   sites. See supplementary data (4) for a description of the different stand types.
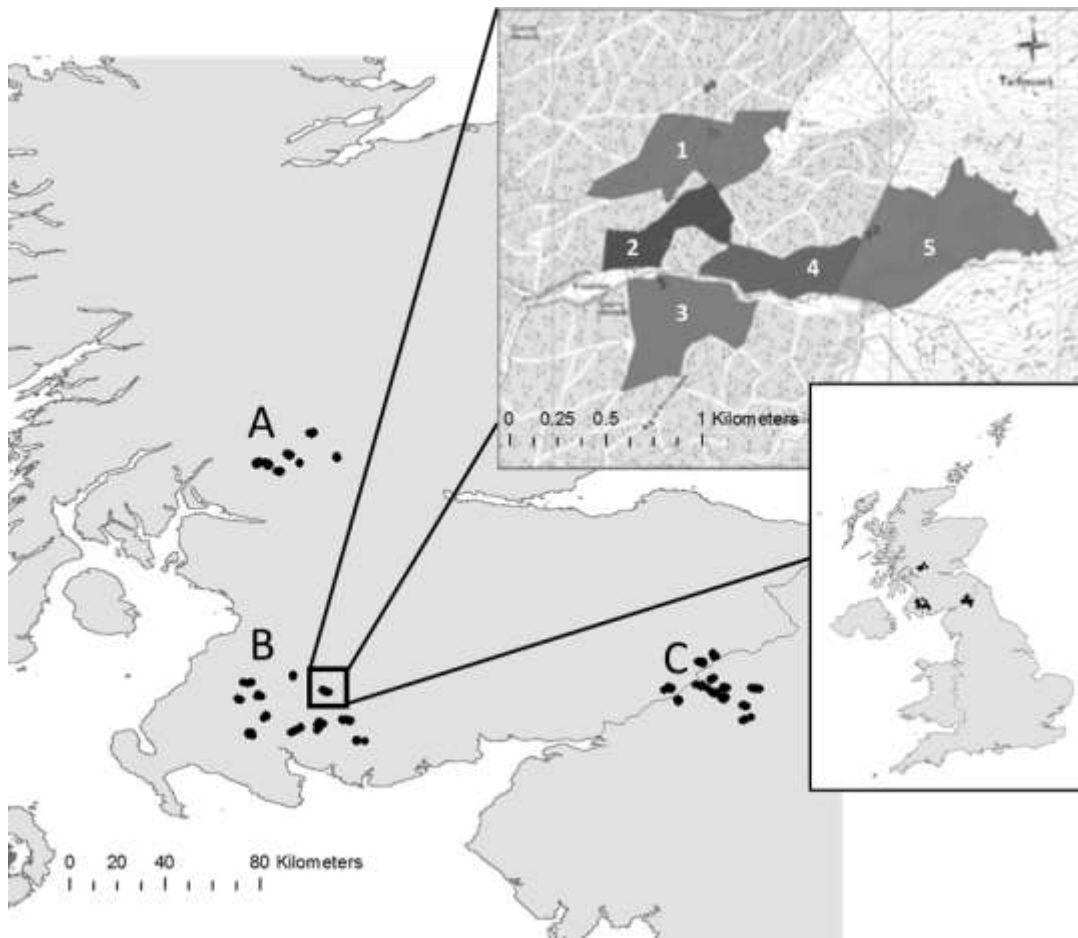
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150 Figure 1. Location of field sites at three different study areas in (A) Cowal and Trossachs, South West

151 Scotland, (B) Galloway, South West Scotland and (C) Kielder, Northern England. Stand types were as

152 follows: Clearfell (1), Young (2), Thicket (3), Thin (4), Mature (5). See Supplementary data 4 for stand

153 details.

154 *2.1 Invertebrate trapping*

155 Each site was surveyed for one night. Moths were trapped using portable 6W heath light traps using

156 E7586 9'' actinic tube lights, powered with 12V batteries which were activated 15 mins after sunset

157 and switched off after 4 hours (approximating the duration of the shortest night in the study area).

158 This ensured that species flying at dusk and during the night were surveyed regardless of night

159 duration. Species flying at dawn would most likely be missed as traps were often turned off before

160 dawn. Surveys were only conducted on nights that were above 8°c in temperature and wind speed

161 of less than Beaufort 4, and were randomised as far as possible during the survey season between

162   the different geographical areas. We recognise that surveying each site only once provides a coarse

163   estimate of local moth assemblages; however, we are primarily interested in comparisons between

164   stand types to identify potentially influential characteristics, which requires a large sample size. This

165   same approach has been used to identify the influence of woodland characteristics on species

166   richness, diversity and abundance of moth populations in both agricultural and urban landscapes

167   (Fuentes-Montemayor et al. 2012; Lintott et al. 2014). In addition, previous studies have suggested

168   that patterns of moth community composition remain consistent despite seasonal turnover

169   (Summerville and Crist 2003).

170   Within each stand a heath trap was placed 15 metres from the edge, at least 200m from the

171   next nearest trap and the location recorded with a GPS. Traps were selectively positioned to ensure

172   that similar light levels were emitted (e.g. avoiding vegetation obscuring the light). In most cases, the

173   traps were not visible from each other, apart from in felled stands. This may introduce a bias in traps

174   at felled sites as the lights were visible from further away, reducing spatial independence (Lacki et al.

175   2007) although the attraction radii of heath light traps is commonly only between 10 – 30m

176   depending on moth family (Truxa & Fiedler 2012). Any moths attached to the outside of the trap at

177   the end of the trapping session were gently removed and released. A cotton wool ball soaked in

178   ethyl acetate was immediately added to the trap and left overnight to kill trapped invertebrates.

179   Macro moths were removed and pinned to boards for later identification and micro moths were

180   separated for identification by an expert at the National Museum of Scotland. Approval for this work

181   was obtained from the Ethical Review Committee within the Department of Biological &

182   Environmental Sciences at the University of Stirling. Species data were shared with local moth

183   recorders and added to the National Moth Monitoring Scheme (Fox et al. 2010).

184   *2.2 Local habitat characteristics*

185   We carried out vegetation surveys in two 0.01 ha plots at each stand type; due to the homogenous

186   nature of stands these plots were considered representative of the stand as a whole. At each plot we

187   recorded the total number of trees with diameter at breast height greater than 7 cm (stand density)

188   and recorded the dominant ground cover (vegetated / non vegetated). Since dead wood is

189   important for saproxylic moths we assessed the amount of dead wood on the forest floor using the

190   following scale: 0 – no coarse woody debris, 1 – small twigs, 2 – large twigs and branches over 7cm

191   in diameter, 3 – both large and small branches. Understory vegetation height was measured at 10

192   evenly spaced points across the radius of the circle and canopy cover was recorded at each point

193   using a sighting tube with an internal crosshair; if the crosshair intersected with any canopy

194   vegetation presence of canopy cover was recorded and converted to a percentage cover score

195   (Lintott et al. 2015).

196   *2.3 Landscape analysis*

197   The GUIDOS toolbox (Soille & Vogt 2009) was used to determine percentage cover of core (more

198   than 20m from the edge), and edge (patches within 20m of the edge) broadleaf tree cover woodland

199   and felled patches within 4km of each moth trap by combining data from the OS Mastermap (EDINA,

200   2014) and a high resolution Forestry Commission database specific to the study areas. Distance to

201   both broadleaf patches and felled areas as well as the size of the nearest broadleaf / felled patch

202   were also recorded. It should be noted that broadleaf cover could be remnants of deciduous

203   woodland cover from before the plantation was planted. Finally, the complexity of the broadleaf

204   patch (a score of the total area of broadleaf / felled divided by the total edge area of broadleaf /

205   felled) was calculated which approximates fragmentation (a highly fragmented area will have a high

206   complexity score, see Appendix 1 for details on landscape variables included in analysis).

207   *2.4 Statistical analysis*

208   All analysis was carried out using R (version 3.4, R core development team) using the following

209   packages: MuMIn, lme4, vegan, ggplot2. We used Margalef diversity to assess species diversity as it

210   is straightforward to interpret and because it can deal with occasions where the number of

211   individuals in a trap is equal to the number of species (Magurran 1988).

212   Many of the local and landscape variables were collinear so we used principle components

213   analysis (PCA) to remove collinearity and reduce the number of predictors. Three separate PCAs

214   were conducted for local characteristics and the felling and broadleaf tree cover metrics (See

215   Supplementary data 1 for an explanation of the variables included in the PCA). For each PCA we

216   retained those axes which explained more variation than random using the "broken stick" approach

217   (Jackson 1993). For the local characteristics (Local PC), the first two axes explained 77% of the

218   variation between stands; Local PC1 mainly described the stands with low canopy cover and high

219   understorey vegetation height (which loaded low on PC1) and stands with low vegetation cover and

220   high canopy cover (which loaded high on PC1), loosely catagorising different stand types

221   (Supplementary data 2, Figure A). Local PC2 was driven largely by differences in altitude, describing

222   the difference between the three different forests, with Galloway sites primarily at low altitudes,

223   Kielder stands predominantly at high altitudes and Cowal and Trossachs falling in between. For

224   felling characteristics (Felling PC), only the first axis explained more variation (63%) than chance;

225   stands with low values of Felling PC1 were closer to patches of clearfell and surrounded by greater

226   areas of felling in a 1km radius and those loading high on Felling PC1 were further from felled areas

227   with less overall felling in a 1km radius (Supplementary data 2, Figure C). For characteristics relating

228   to broadleaf woodland in the landscape (Broadleaf PC), only the first axis explained more variation

229   (67%) than by chance; stands loading high on Broadleaf PC1 tended to be further from smaller

230   patches of broadleaf woodland, with less broadleaf tree cover in the surrounding landscape whereas

231   sites loading low on Broadleaf PC1 were closer to larger broadleaf patches, with more overall

232   broadleaf tree cover in the surrounding habitat (Supplementary data, Figure B).

233   Using an information theoretic approach, we assessed the influence of stand and landscape

234   variables on the **abundance** and **species richness** of macro and micro moths separately, using each

235   metric per stand as the unit of replication. We used generalised linear models with a negative

236   binomial error structure to account for overdispersion, and included an interaction between latitude

237   and longitude as a fixed effect in all models to account for spatial autocorrelation. Models were

238 validated by visual assessment of the residuals (Crawley 2007). Continuous variables were

239 standardised and centred around a mean of zero and a standard deviation of 1 to allow direct

240 comparisons of estimates, and model fit was assessed by comparing the change in AIC, retaining the

241 best model (change in AIC greater than 2). McFaddens pseudo R^2 (McFadden 1974) was used to

242 assess the amount of variation explained by each model. Local PC2 was not used, as this mainly

243 described the difference in altitude between the stands and was collinear with date; in all cases

244 simply using date was a better predictor. Models were fitted using either the stand type or the Local

245 PC1, depending on model fit. We assessed the impact of felling and surrounding broadleaf tree cover

246 on each response measure including either Felling PC1 or Broadleaf PC1 separately, then together

247 and as an interaction. The same process was followed for **Margalef diversity** and **dominance** using a

248 Gaussian error distribution. For each response measure, if there was no clear "top" model we

249 averaged the coefficients across the top models in the set which accounted for a change in AIC of

250 less than 2, using full averaged models to reduce the bias from explanatory factors which do not

251 appear in every model (Burnham and Anderson 2002). Explanatory variables were considered to

252 have a "significant" effect on the responses if the standard error of the estimate did not cross zero

253 (Burnham & Anderson 2002). Micro and macro moths were analysed separately. Although the

254 distinction between macro moths and micro moths is not taxonomically supported, micro moths

255 typically have lower dispersal distances apart from some migratory species (Nieminen et al. 1999)

256   In addition to moth community measures outlined above, we modelled the influence of local

257 and landscape characteristics on the occurrence of six of 13 **BAP priority species** recorded in the

258 plantations. The following six species (*Eugnorisma glareosa* (Autumnal Rustic), *Arctia caja* (Garden

259 Tiger), *Celaena haworthii* (Haworths Rustic), *Xestia castanea* (Neglected Rustic), *Ecliptopera silaceata*

260 (Small Phoenix) and *Spilosoma lubricipeda* (White Ermine)) were present at the most sites and

261 represented species which have declined between 70 – 90% over the last ten years (Conrad et al.

262 2006). We had insufficient data to model abundance at stand-level, so presence of these species was

263 modelled using a binomial mixed effects model with species ID as a random intercept and Local PC1

264   as a random slope in order to assess species specific responses to stand level changes. We used the

265   same approach as the previous analyses but here visual inspection of the data and subsequent

266   model checking indicated that species occurrence was strongly and similarly associated with

267   distance to felled areas and the size of broadleaf patches, so these were used in preference to the

268   Felled and Broadleaf PC axis.

269   We graphically present the results for the single best model for each analysis including

270   standardised parameters and standard errors for all explanatory variables. Inferences were made by

271   comparing each parameter's standardised estimate with other predictor variables to assess its

272   relative importance, the upper and lower 95% quantiles of each parameter obtained from N = 2000

273   simulated draws from the estimated distribution (Lintott et al. 2014) and a comparison of selected

274   models using AIC.
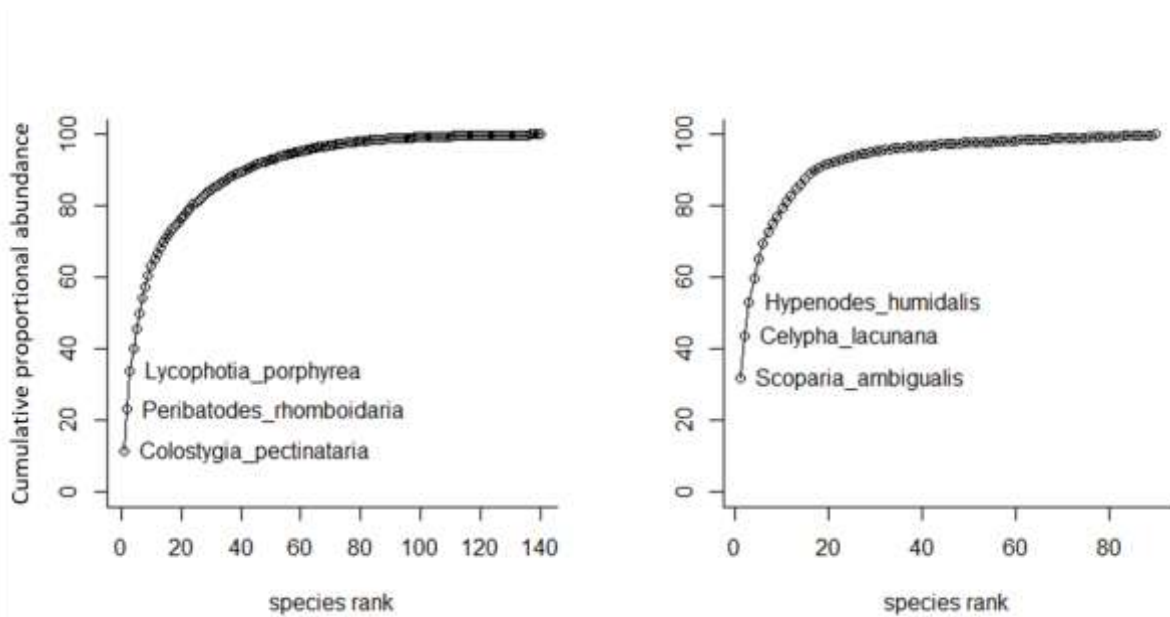
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276   Figure 2. Species rank abundance curves for macro and micro moths considered separately. The

277   three most abundant species are named. Rank abundances are given as cumulative proportions of

278   total abundance.

3. Results

Composition of moth populations in commercial coniferous plantations

We collected a total of 8074 moths comprising 6464 macro moths belonging to 140 species and 10 families, and 1762 micro moths, belonging to 90 species and 19 families (Supplementary data 1) over 170 trap nights. Of these, 60% were generalist species while only 14% were woodland specialists and 26% were associated with open habitats (open specialists). We recorded an average of 38 (± 4.2) macro moth species and 10 (± 1.5) micro moth species per stand. Community composition was dominated by a few, highly abundant species such as the micro moth *Scoparia ambigualis* (Crambidae) and the macro moth *Colostygia pectinataria* (Geometridae), with less than 20% of micro moth species accounting for over 80% of all micro moths collected and 34% of macro moth species accounting for over 80% of all macro moths (Figure 2). We recorded 13 BAP priority species, with an average of 3.2 ±0.6 per stand.

3.1 Influence of local characteristics on moth communities

After accounting for date and temperature, there was relatively little correlation between local characteristics and moth communities (Table 1), with correlations between Local PC1 and macro moth abundance only. Abundance was highest in stands with a low Local PC1 score (low canopy cover and high understorey vegetation height), falling 53% in older stands with a closed canopy and lower understory vegetation height. Fewer moths of both groups were collected later in the season, with a similar pattern for species richness and diversity, but not dominance. Finally, the interaction between latitude and longitude influenced richness, abundance and diversity for micro moths but not macro moths (Table 1) revealing regional differences in species richness and abundance, with the highest abundance in Galloway plantation (27.0 ± 3) and lower in Kielder (13.0 ± 1.6) and Cowal and Trossachs (8.5 ± 1.3).

Table 1. Best approximating GLM's assessing influence of local, felling and broadleaf parameters on moth richness, abundance, diversity and dominance, conducted using an information theoretic approach with model averaging to assess importance of parameters. NA's indicate parameters not included in the top model sets. Dominant ground cover, coarse woody debris and the interaction between Felling PC1 and Broadleaf PC1 was never included in any top models and are not presented here. Parameters in bold are those which have a significant effect on response values, determined by whether the standard error of the estimate crosses zero (Burnham & Anderson 2002). Akaikes weight is the total weight explained by all models. Averaged estimates are presented ± the standard error.

		No. models averaged across	Intercept	Local PC1	Felling PC1	Broadleaf PC1	Date	Temp	Lat:Long	Akaike's weight
Macro moths	Sp. Richness	7	**264.9 ± 177.6**	**-0.70 ± 0.20**	**0.27 ± 0.08**	**-0.10 ± 0.00**	**-0.35 ± 0.11**	0.01 ± 0.05	0.27 ± 0.34	0.62
	Abundance	5	**3.21 ± 0.17**	**-0.26 ± 0.11**	**0.49 ± 0.12**	**-0.38 ± 0.17**	**-0.61 ± 0.19**	0.16 ± 0.16	0.21 ± 0.39	0.63
	Marg. Diversity	6	**2.01 ± 0.18**	-0.11 ± 0.12	**0.34 ± 0.11**	**-0.33 ± 0.14**	**-0.39 ± 0.15**	0.02 ± 0.07	0.30 ± 0.42	0.64
	Simp. diversity	9	**1.22 ± 0.19**	-0.04 ± 0.12	-0.03 ± 0.10	NA	0.08 ± 0.21	0.04 ± 0.11	NA	0.27
Micro moths	Sp. Richness	4	**1.23 ± 0.15**	-0.02 ± 0.06	**0.24 ± 0.09**	**-0.28 ± 0.11**	-0.10 ± 0.13	**0.33 ± 0.10**	**1.54 ± 0.40**	0.77
	Abundance	2	**2.28 ± 0.20**	NA	**0.47 ± 0.12**	**-0.45 ± 0.17**	-0.32 ± 0.25	**0.42 ± 0.15**	**1.93 ± 0.50**	0.73
	Marg. Diversity	4	**1.07 ± 0.10**	-0.01 ± 0.03	**0.13 ± 0.06**	-0.14 ± 0.10	-0.13 ± 0.10	**0.30 ± 0.07**	**0.86 ± 0.24**	0.65
	Simp. diversity	13	**0.75 ± 0.17**	-0.04 ± 0.11	NA	0.01 ± 0.05	-0.03 ± 0.11	0.10 ± 0.16	NA	0.43

310 Table 2: Best approximating GLM's assessing influence of local, felling and broadleaf parameters on BAP moth species probability of being detected. These

311 were conducted using an information theoretic approach with model averaging to assess importance of parameters. NA's indicate parameters which were

312 not included in the model. Dominant ground cover, coarse woody debris and the interaction between Felling PC1 and Broadleaf PC1 was never included in

313 any top models and is not presented here. Parameters in bold are those which have a significant effect on response values, determined by whether the

314 standard error of the estimate crosses zero (Burnham and Anderson 2002). Akaikes weight is the total weight explained by all models. Estimates for the full

315 averaged model are presented ± the standard error. Estimates provided for the top 7 models, with a change in AIC of less than 2. The same variables as for

316 the overall moth communities were originally used but inspection of the broadleaf and felling PC output showed that the main relationships were with

317 specific components of the principle components.

	Intercept	Size of nearest broadleaved patch	Altitude	Distance to felled stand	Lat:Long	Local_PC1	AICc	Akaikes weight
Averaged Model	**-2.88 ± 0.25**	**0.22 ± 0.09**	-0.04 ± 0.10	**0.16 ± 0.14**	0.02 ± 0.09	-0.44 ± 0.35		0.50
1	-2.95	0.22	NA	0.22	NA	-0.59	479.90	0.13
2	-2.92	0.22	NA	NA	NA	-0.53	480.92	0.08
3	-2.97	0.23	-0.13	0.24	NA	-0.59	480.96	0.07
4	-2.67	0.21	NA	0.21	NA	NA	481.17	0.07
5	-2.96	0.23	NA	0.20	0.09	-0.59	481.53	0.06
6	-2.98	0.27	-0.22	0.21	0.18	-0.59	481.56	0.05
7	-2.67	0.21	NA	NA	NA	NA	481.82	0.05

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319

320   *3.2 Influence of felling on moth communities*

321   There appeared to be a large, negative impact of clear felling on species richness, abundance and

322   diversity for both macro- and micro moths (Figure 3, Table 1). Macro moth species richness declined

323   from 13.4 (9.3 – 19.4) in sites furthest from clear felled areas and with less felling within 1km to 4.0

324   (2.5 – 6.6) in sites nearest to felled areas or surrounded by more felling in 1km. Similarly, micro moth

325   species richness fell from 4.2 (2.9 – 6.2) to 1.5 (0.9 – 2.5) in sites close to felling or with a greater

326   proportion of felling in the surrounding landscape (Figure 3 A, D).
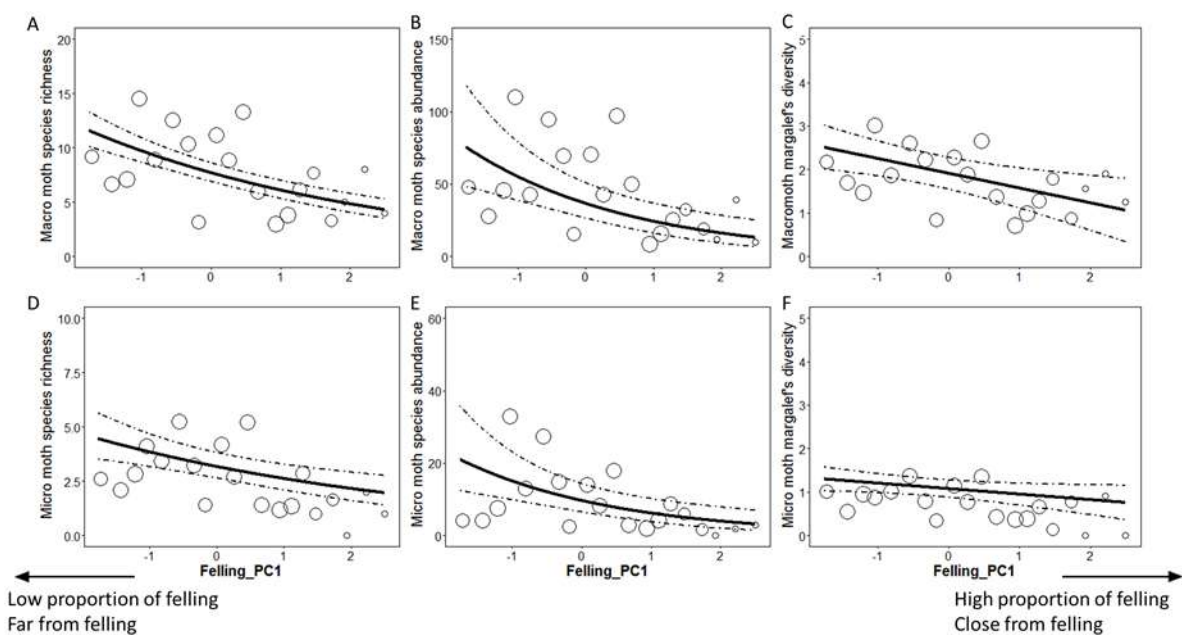
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329   Figure 3. Impacts of felling on (A – C) Macro moth species richness, abundance and diversity and (D

330   – F) Micro moth species richness, abundance and diversity per site. Different scales are used for

331   abundance and richness due to higher richness and abundance in macro moths compared to micro

332   moths. Original data on richness, abundance and diversity are superimposed as grey circles with

333   diameter proportional to the number of sampling points where mean values occurred. Dashed lines

334   represent 95% confidence intervals around the predictions (solid line).

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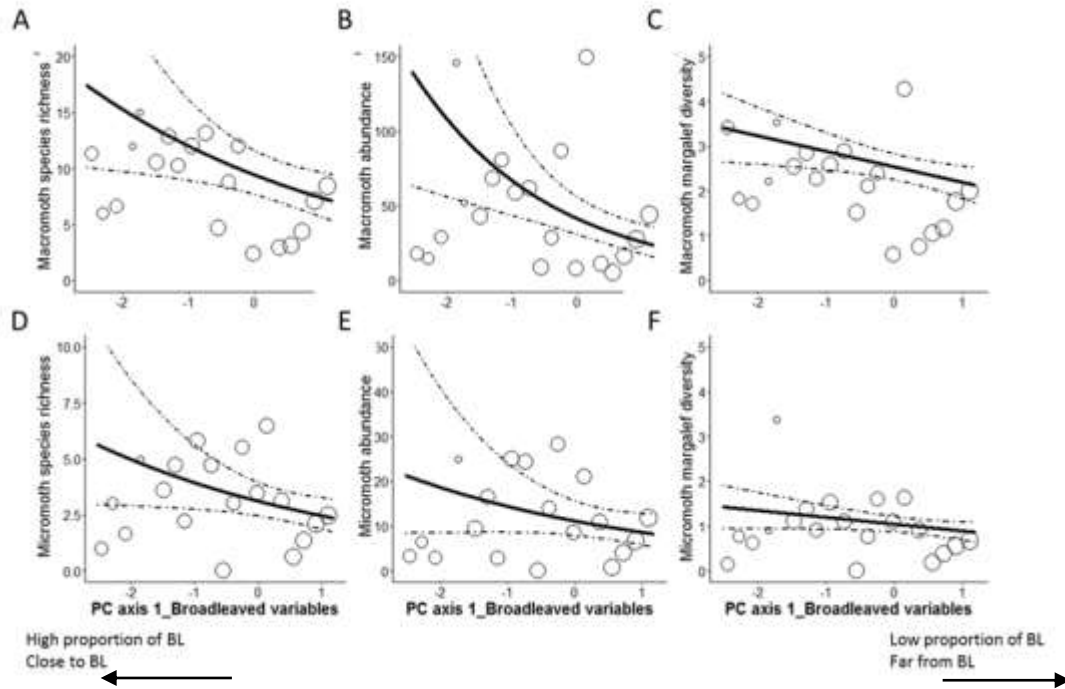
Fig. 4. Impacts of the amount and proximity of broadleaf woodland (BL) on (A – C) Macro moth

species richness, abundance and diversity, and (D – F) Micro moth species richness, abundance and

diversity per stand. Different scales are used for abundance and richness due to higher richness and

abundance in macro moths compared to micro moths. Original data on richness, abundance and

diversity are superimposed as grey circles with diameter proportional to the number of stands

where mean values occurred. Dashed lines represent 95% confidence intervals around the

predictions.

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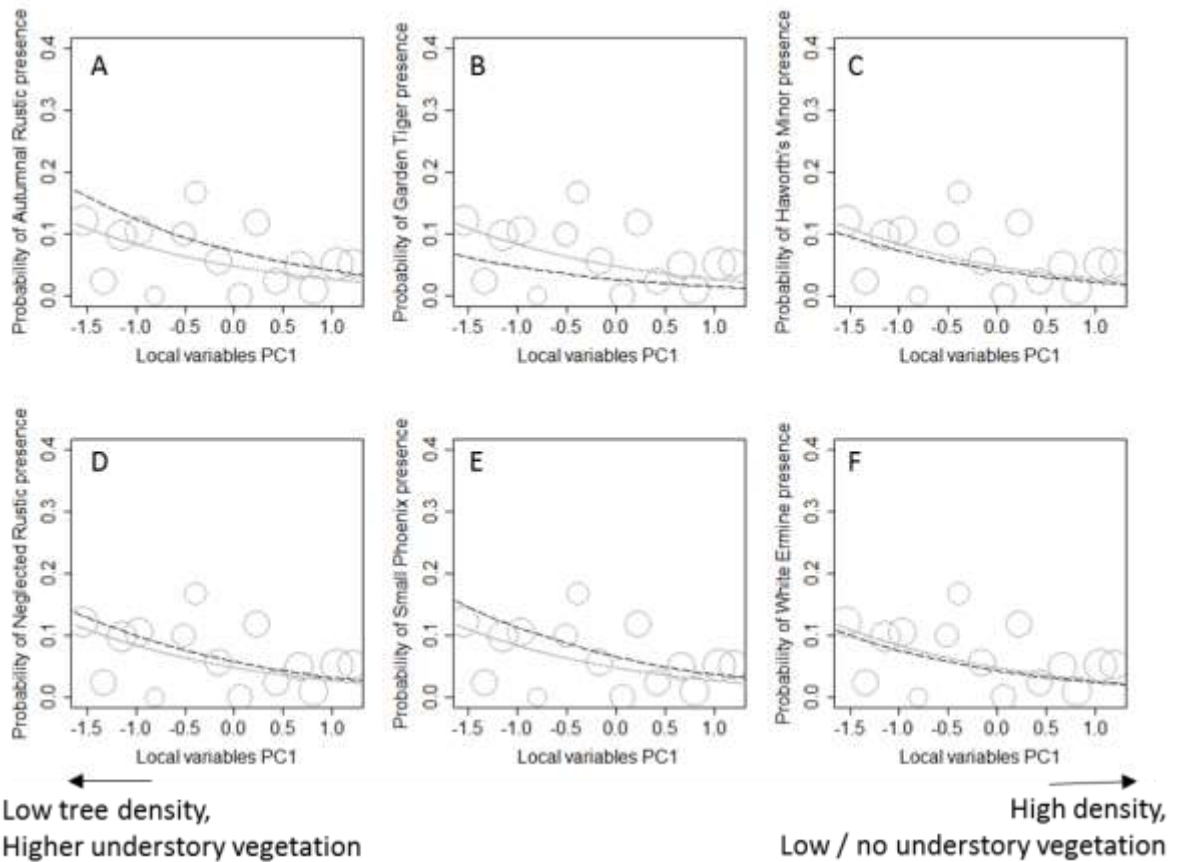
Figure 5. Probability of recording priority BAP species by Local PC1 scores (associated with a shift

from stands with low canopy cover and taller vegetation height to stands with high canopy cover

and low vegetation height). Sites low on PC1 are predominantly clear fell and young, moving to

thinned and mature aged stands loading high on PC1. Dotted lines are species specific, whilst the

grey line shows the trend across all six BAP species. Original data on richness, abundance and

diversity are superimposed as grey circles with diameter proportional to the number of stands

where mean values occurred.

Both micro and macro moth abundance responded strongly to Felling PC1; macro moth abundance

decreased from 68.0 (40.0 – 114.0) moths in sites far from felling or with a low proportion of felling

in the surrounding landscape to 10.0 (5. 4 – 18.5) in sites closer to felling or with more felling in the

surrounding landscape, and micro moth abundance decreased from 25.0 (14.0 – 42.0) individuals to

363   2.5 (1.3 – 4.9) individuals (Figure 3 B, E). There was little response of diversity of either group to the

364   proximity or prevalence of felling (Figure 3 C, F).

365   *3.3 Effects of the presence of broadleaf tree cover on moth communities*

366   In general, the proximity and amount of broadleaf tree cover within 4km of sampling sites appeared

367   to be positively associated with species richness, abundance and diversity for both macro and micro

368   moths, although the effect was smaller than the impact of felling (Table 1, Figure 4). The effect is

369   clearest for species richness, with richness of macro moths in stands nearest to the largest patches

370   of broadleaf tree cover double that of stands furthest from smaller patches of broadleaf, increasing

371   from 7.0 (5.0 – 9.0) species to 15.0 (8.0 – 29.0) species per stand (Figure 4 A). Similarly, micro moth

372   richness increased from 2.5 (1.3 – 3.1) species in stands far from broadleaf tree cover and with a low

373   proportion of broadleaf in the surrounding area to 5.0 (3.0 – 10.0) species richness in stands closest

374   to broadleaf patches or with a high proportion of broadleaf tree cover in the surrounding landscape

375   (Figure D). Whilst the influence of broadleaf woodland on abundance of both groups is similar, the

376   relationship appears to be weaker than for species richness (Figures 4B, E), and for macro moths

377   appears to be driven by high abundance at one site (Figure 4 B). Neither local variables, felling nor

378   broadleaf characteristics had any correlation with macro or micro moth dominance.

379   *3.4 Influence of local characteristics, felling and broadleaved woodland on BAP priority species*

380   The likelihood of catching a BAP species increased further from felled areas, and as the size of the

381   nearest broadleaf patch increased, with all six species having very similar response to both variables.

382   However, the correlation of Local PC1 with micro moth presence differed between the BAP priority

383   species. *Eugnorisma glareosa* (Autumnal Rustic; Figure 5 A) and *Ecliptopera silaceata* (Small Phoenix;

384   Figure 5 E) responded relatively strongly to Local PC1, and were more likely to be recorded in open

385   stands with taller vegetation whereas there was relatively little change in the probability of capture

386   for *Arctia caja* (Garden Tiger; Figure 5 B).

4. Discussion:

Here, we demonstrate that plantations can support large communities of moths, including several BAP priority species. Lepidoptera are one of the most abundant and diverse insect orders, but are currently undergoing widespread declines across Europe (Fox et al. 2013). Loss of habitat and changes to silvicultural practices in native woodlands have been cited as drivers of these losses, but to date the value of coniferous plantations for moths has been ignored due to their perception as being a poor habitat for biodiversity.

Moth abundance was dominated by generalist species which are preferentially found in heath or bog habitats, or by a small number of conifer specialist species. Macro moth abundance was highest in relatively low density stands with vegetation cover, which are more likely to support appropriate larval host plants, compared to dense stands with predominantly bare or moss as dominant ground cover. In addition, sites loading low on Local PC1 were often recently felled and young stands with large amounts of dead wood remaining which would benefit saproxylic species (Thorn et al. 2015). However, we saw no effect of stand characteristics on species richness or diversity in macro moths or for any micro moth response metric, possibly because we captured a high proportion of generalist moth species which have less strict habitat associations. We have no data on the species composition of moth communities prior to afforestation but it is likely to include species which specialise on low nitrogen, open habitats.

Felling was strongly and negatively correlated with both macro- and micro moth species richness, abundance and diversity. Macro and micro moth species richness was three times higher in sites furthest from felling, and with fewer felled patches in the immediate landscape, whereas abundance for macro and micro moths was between 7 and 10 times higher in sites further from felling and with less felling in the surrounding landscape. This reflects patterns reported from managed native broadleaf forests in Indiana, which found that clear felling significantly reduced moth species richness compared to either no management or selective felling (Summerville & Crist

412 2002). Clear felling causes substantial changes in the floristic composition of the forest habitat and

413 through substantial changes in microclimate, to herbaceous ground cover and host plant availability

414 (Summerville 2011). Summerville (2011, 2013) similarly found that species richness of moths was

415 40% lower after timber removal, with the impacts of felling persisting up to 200m from the cleared

416 site itself.

417   The nature of the landscape matrix stands are embedded in may impede or facilitate

418 dispersal between habitat types (Tscharntke et al. 2012); if there is too much felling in the

419 surrounding landscape it may impede moth movements. Felled stands themselves may still be

420 attractive to particular moth species due to intermediate levels of disturbance allowing pioneer and

421 to some degree specialist species to coexist (Hamer et al. 2003). Indeed, in simplified landscapes,

422 characterised by high disturbance, dynamics in habitat patches are likely to be determined by the

423 availability of landscape wide remnant communities, particularly for species able to disperse over

424 wide distances (Tscharntke et al. 2012).

425   Disturbed habitats are often characterised by a high abundance of a few generalist species,

426 with the same subset of taxa dominating local stands and at the regional level. The majority of the

427 moths we trapped were generalist species (Supplementary data 1), this may reflect the fact that

428 moths using the plantations are those which can persist in a disturbed environment, as generalist

429 species are more resilient to disturbance (Franzén & Johannesson 2007). For example, although 14%

430 of all the moths we recorded are deciduous specialist feeders, the tree species they specialise on are

431 often planted as deciduous tree cover in plantations (Tallamy & Shropshire 2009). It is not possible

432 to tell from our study whether moth populations in plantations differ significantly from those in

433 native broadleaf woodlands. However, due to the levels of disturbance caused by felling and the

434 potential lack of host plants, as well as the predominance of generalist species we found in our

435 plantation sites, we would expect plantation woodlands to support a less diverse moth population

436 than broadleaf woodlands do. Macro moth species richness in the plantations was similar to that

437 found in broadleaf woodlands within an agricultural matrix, although abundance was lower, while

438 micro moth richness was 25% higher than in agricultural woodlands (Fuentes-Montemayor et al.

439 2012). Micro moth richness was similar to that reported from urban woodlands, but macro moth

440 richness was 40% higher in plantations (Lintott et al. 2014). It is surprising that similar or lower

441 species richness and abundance was found in urban (Lintott et al. 2014) and agricultural woodlands

442 (Fuentes-Montemayor et al. 2012). It would be interesting to determine whether this is due to

443 geographical differences (sites surveyed by Fuentes-Montemayor et al. 2012, and Lintott et al. 2014

444 were in Scotland but further north than the majority of sites surveyed for this study) or whether

445 woodlands surrounded by agricultural and urban land are similarly disturbed habitats due to a more

446 hostile matrix (Tscharntke et al. 2012), although the drivers of disturbance may differ.

447   Continuous cover forestry, which involves the continuous and uninterrupted maintenance of

448 forest cover and avoids clear felling (Pommerening & Murphy 2004), has been advocated as an

449 alternative forest management system. The UK forest standard requires managers to identify areas

450 "which can be managed under a continuous cover forestry system and build them into forest design"

451 (Mason et al. 1999). Despite not being appropriate for widespread use in all plantation forests due

452 to the potential risk of wind damage to stands, there is evidence to suggest that multi aged systems

453 may be more resilient to impacts of wind (O'Hara & Ramage 2013) and the potential forest health

454 and yield benefits are increasingly recognised, with over 10% of Forestry Commission woodlands

455 now under continuous cover management (Macdonald et al. 2009; O'Hara & Ramage 2013).

456 Switching to continuous cover forestry may benefit moth communities; in Indiana (USA) Summerville

457 et al (2009) found that shelterwood harvesting (removal of 15% biomass and similar in concept to

458 continuous cover forestry) did not reduce functional and compositional resilience of lepidopteran

459 communities compared to group selection harvesting (80% of tree biomass removed) and clear

460 felling which had a significant negative impact. Additionally, moth communities showed signs of

461 recovery within three years compared to other studies showing impoverished moth communities up

462 to 60 years after clear felling (Summerville 2013; Summerville et al. 2009)

463 We found that the amount and proximity of broadleaf tree cover positively influenced moth species

464 richness, and to some extent abundance. Many native tree species such as *Betula*, *Quercus* and *Salix*

465 have large numbers of moth species associated with them (Tallamy & Shropshire 2009) and are

466 commonly planted in conifer plantations as broadleaf regeneration trees. Fuentes-Montemayor et al

467 (2012) found that species richness was highest in woodland with no conifers, so increasing landscape

468 heterogeneity by planting patches of broadleaf tree cover within the plantation landscape may be

469 invaluable islands allowing moth species to persist within the plantation matrix despite felling

470 disturbance.

471 We recorded 13 BAP priority species using plantation woodlands. BAP priority species are so

472 designated due to their rapidly declining populations across the United Kingdom and the need for

473 further scientific study in order to assess and understand their population declines (Conrad et al.

474 2006). Of these, seven were present in fewer than 10 sites and were removed from further

475 modelling. Of the six remaining species, all are habitat generalists or conifer and moorland habitat

476 specialists. These species responded to stand type characteristics (separated by local PC1)

477 differently. The Autumnal Rustic (*Eugnorisma glareosa*) and the Small Phoenix (*Ecliptopera silaceata*)

478 were most likely to be detected in open stands with low canopy cover and stand density; the

479 Autumnal Rustic is a generalist species often associated with moorland habitats which constitute a

480 large proportion of the surrounding landscape and the Small Phoenix is a conifer specialist, and

481 therefore likely to thrive in conifer plantations. All BAP species were significantly less likely to be

482 recorded in stands closer to felled areas regardless of the size of the felled area or the proportion of

483 felling in the surrounding area which, considering the two species' preference for open stands is

484 somewhat surprising. All BAP species also responded equally positively to the size of the nearest

485 patch of broadleaf tree cover. Broadleaf patches within plantations are not part of active harvesting

486 programs, and are maintained or increased to meet biodiversity and restructuring guidelines (Watts

487 et al. 2008), so may provide a potential source from which moth species can disperse.

488   *4. 1 Management recommendations:*

489   Worldwide, forest managers increasingly recognise the importance of sustainable forest

490   management to improve biodiversity, but exotic pine plantations have received relatively little

491   attention for their potential contribution to moth communities above and beyond the impacts of

492   pest moth species. However, we found similar or higher levels of abundance and diversity compared

493   to fragmented urban and agricultural woodlands in nearby regions (Lintott et al. 2014; Fuentes-

494   Montemayor et al. 2012), and more BAP priority species in conifer plantations than urban

495   woodlands (Lintott et al. 2014). We found that moth richness, abundance and diversity were

496   influenced by plantation management and consider that the following should be taken into account

497   when considering how plantation management may affect moth communities:

498   **1. Switching to continuous cover forestry:**

499   Similar to other studies in native woodlands under felling pressure (Summerville 2014;

500   Summerville 2011; Summerville & Crist 2002; Summerville 2013; Summerville et al. 2009), felling

501   significantly affected moth populations in our study sites, reducing species richness and

502   abundance. Since clear felling was the only timber extraction technique used at our sites we

503   were not able to compare with other lower-intensity methods. Switching to continuous cover

504   forestry where appropriate will benefit moth communities and in turn the small mammal, bird

505   and bat species which rely on them as a prey source while not negatively impacting forest

506   productivity (Macdonald et al. 2009).

507   **2. Maintaining broadleaf woodland:**

508   Moth abundance and richness was far higher close to broadleaf tree cover; continued replanting

509   of broadleaf trees and reduced intensity of management where possible near broadleaf stands

510   should benefit both micro and macro moth richness and abundance. Many moth species can

511   only disperse over relatively short distances (Merckx et al. 2012), therefore increasing the

512   amount and connectivity of broadleaf woodland may allow moth species to persist within and

513   disperse throughout plantations. All BAP priority species responded strongly to the size of the

514   nearest patch of broadleaf tree cover, so reducing forestry operations near large patches of

515   broadleaf trees is likely to benefit moth communities in general and BAP species in particular.

516   **3.   Monitoring BAP priority species in plantations:**

517   Of all the BAP priority species, the Garden Tiger (*Arctia caja*) moth was of particular interest as it

518   is a conspicuous species that has declined widely across the UK, possibly due to climatic changes

519   such as warmer wetter winters (Conrad 2002). More northerly habitats may be essential for the

520   persistence of this species, and low density plantation stands may be an important refuge for

521   this species in the face of future climate change. In addition, the Autumnal Rustic (*Eugnorisma*

522   *glareosa*) which was abundant in plantation sites, has undergone substantial declines

523   throughout the UK, thought to be related to pesticide use. Plantation sites should be included in

524   long term monitoring programs to understand further how BAP priority species are using

525   plantation woodlands.

526   Moth populations in Sitka spruce plantations appear to be predominantly generalist species, which

527   may imply a disturbed community (Summerville et al. 2009). However, the presence of some BAP

528   species demonstrates the importance of surveying sites that may historically be perceived as poor

529   for biodiversity. With sympathetic management, plantation forests may have a role to play in

530   preserving and supporting moth populations, particularly as climate change may result in changing

531   species distributions.

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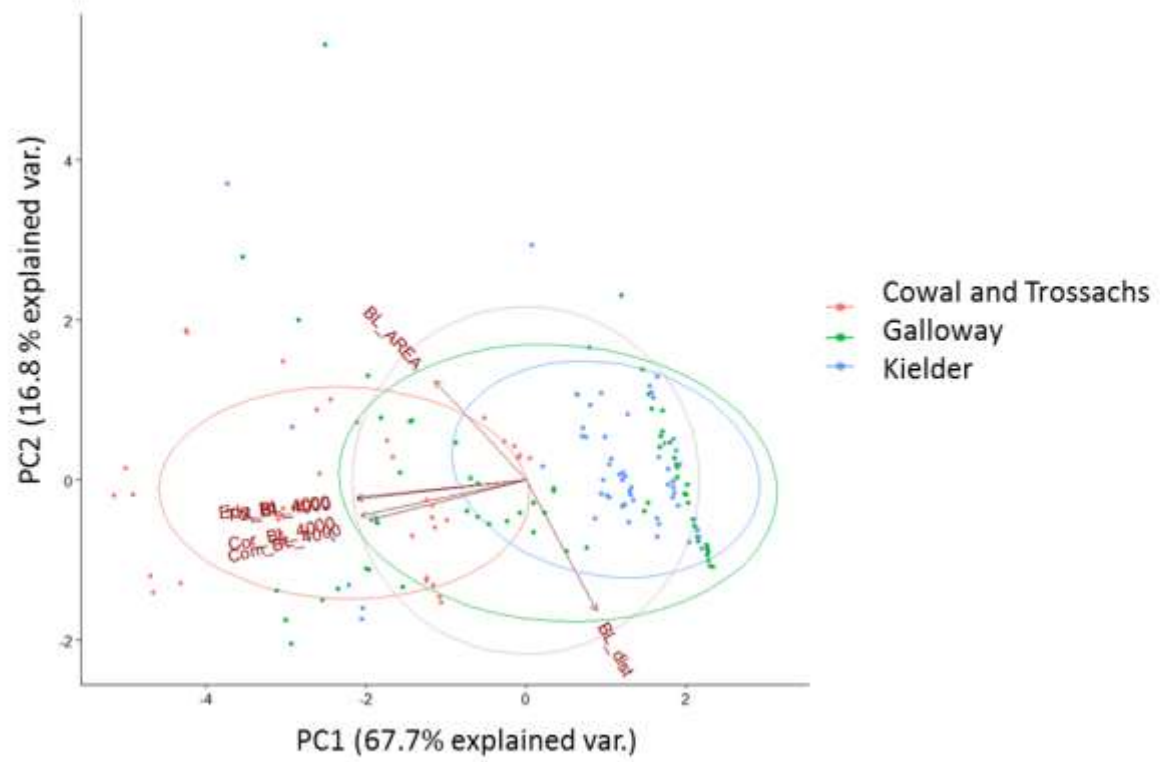
Supplementary data 1:

Table 1: Variables included in Principle Components Analysis.

PC axis	Measure	Unit	Minimum	Maximum	Median	Description
Local PC1	Altitude	m	83.8	466	230.7	Height above sea level
Local PC1	Density	trees per ha	0	3000	600	Number of trees per hectare
Local PC1	Veg height	mm	0	1744.1	156.6	Height of vegetation measured at 10 points across plot
Local PC1	Canopy cover	%	0	1	0.67	Total canopy cover as a percent
Local PC1	Stand Age	years	0	133	14	Stand age calculated from year of planting
Broadleaf PC1	BL_distance	m	0	3934	682	Distance in metres to nearest patch of mature broadleaf
Broadleaf PC1	BL_area	m2	0.1	163.2	1.3	Size of nearest mature broadleaf patch
Broadleaf PC1	Tot_BL_4000	%	0	11.3	0.8	Total broadleaf cover as a % of a 4km2 circle
Broadleaf PC1	Edge_BL_4000	%	0	2.9	0.2	Edge broadleaf cover as % of a 4km2 circle
Broadleaf PC1	Core_BL_4000	%	0	4.9	0.05	Core broadleaf (at least 10m from an edge) as a % of a 4km2 circle
Broadleaf PC1	Com_BL_4000	%	0	2.1	0.3	Total area / Edge area - complexity of cover within the landscape
Felled PC1	FE_distance	m	0	2670	527	Distance in metres to nearest felled stand
Felled PC1	FE_area	m2	0.04	92	13.9	Size of nearest felled stand
Felled PC1	Tot_FE_4000	%	0	35	5.1	Felled cover as a % of a 4km2 circle
Felled PC1	Edge_FE_4000	%	0	8	1.9	Edge felled cover as % of a 4km2 circle
Felled PC1	Core_FE_4000	%	0	26.5	2.4	Core felled (at least 10m from an edge) as a % of a 4km2 circle
Felled PC1	Com_FE_4000	%	0.8	2.1	1.5	Total area / Edge area - complexity of cover within the landscape

Supplementary data 2. Output from principle components analysis:
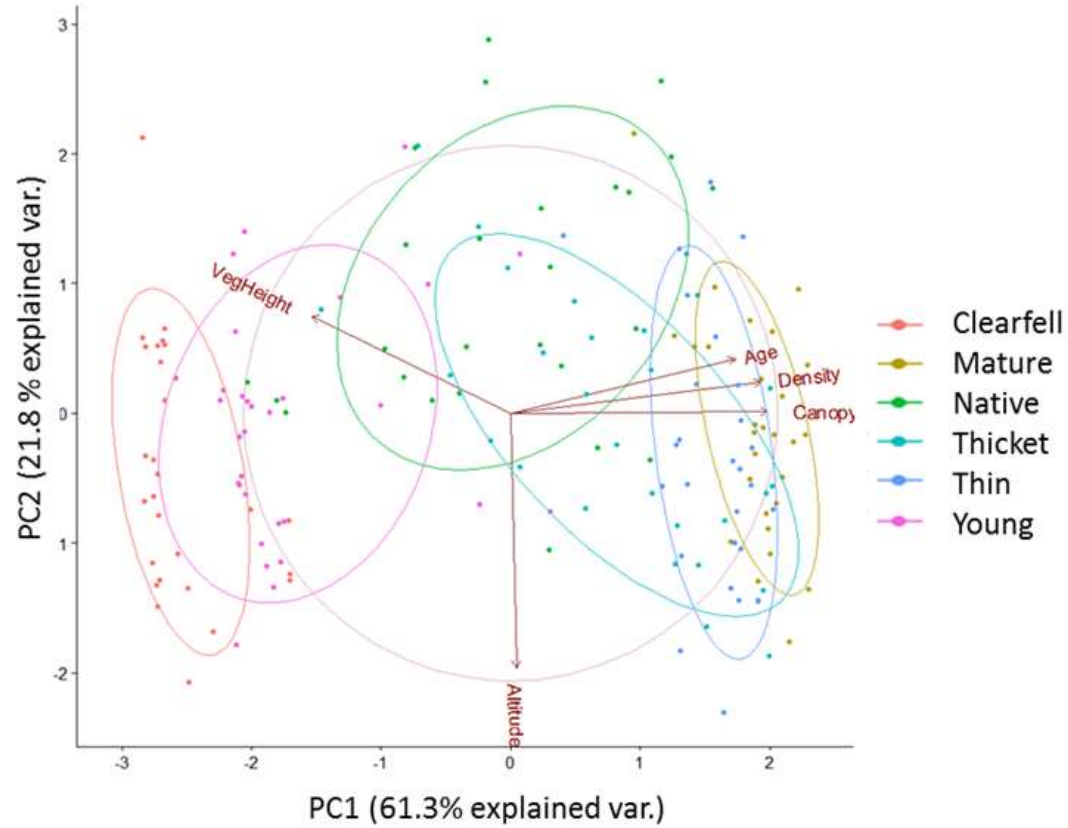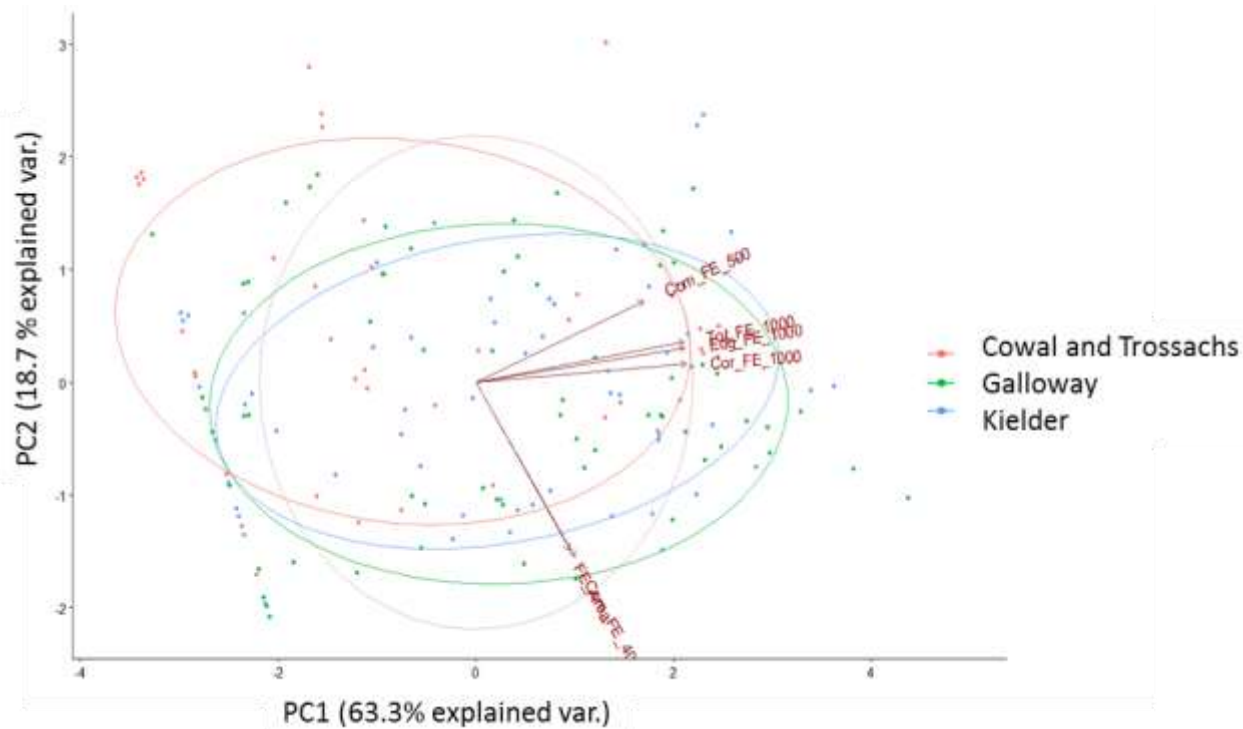
Figure 1. Principle components loadings for A) Local variables, B) Broadleaf variables and C) Felling variables. (see Supplementary data 1 for a description of the variables included in each PCA). Sites are coloured by stand type (Local PC) and by plantation (Broadleaf PC and Felling PC). Coloured ellipses delineate sites within each plantation that are similar to each other based on a normal probability distribution of 0.68. Dark red ellipsoid encompasses sites across all three plantations within a normal probability distribution of 0.68. Arrows indicate direction and magnitude of relationship, variables that are close together or directly opposite are highly correlated.

Supplementary data 3: Full list of moth species recorded as part of study

Table 1: Macro moth species:

Common name (Family)	Latin Name	Abundance per trap (± SE)	Habitat preference
Antler Moth (Noctuidae)	*Cerapteryx graminis*	0.24 ± 0.08	Grassland
Autumnal Rustic (Noctuidae)[a]	*Eugnorisma glareosa*	0.47 ± 0.17	Generalist
Barred Chestnut (Noctuidae)	*Diarsia dahlii*	0.01 ± 0.01	Deciduous
Barred Red (Geometridae)	*Hylaea fasciaria*	1.21 ± 0.33	Conifer
Barred Straw (Geometridae)	*Gandaritis pyraliata*	0.34 ± 0.13	Generalist
Barred Umber (Geometridae)	*Plagodis pulveraria*	0.01 ± 0.01	Deciduous
Beautiful Carpet Moth (Geometridae)	*Mesoleuca albicillata*	0.04 ± 0.02	Deciduous
Beautiful Golden Y (Noctuidae)	*Autographa pulchrina*	0.39 ± 0.10	Generalist
Bordered Beauty (Geometridae)	*Epione repandaria*	0.01 ± 0.01	Deciduous
Bordered Gothic (Noctuidae)	*Sideridis reticulata*	0.01 ± 0.01	Open ground
Bordered Pug (Geometridae)	*Eupithecia succenturiata*	0.01 ± 0.01	Generalist
Bordered Sallow (Noctuidae)	*Pyrrhia umbra*	0.02 ± 0.01	Grassland
Bordered White (Noctuidae)	*Bupalus piniaria*	0.07 ± 0.03	Conifer
Bright Line Brown Eye (Geometridae)	*Lacanobia oleracea*	0.02 ± 0.01	Generalist
Brimstone Moth (Noctuidae)	*Opisthograptis luteolata*	0.04 ± 0.03	Generalist
Broom Moth (Crambidae)	*Ceramica pisi*	0.12 ± 0.05	Moorland
Brown Rustic (Arctiidae)	*Elophila nymphaeata*	0.17 ± 0.11	Deciduous
Buff Ermine (Erebidae)	*Spilosoma lutea*	0.08 ± 0.03	Generalist
Buff Footman (Notodontidae)	*Eilema depressa*	0.19 ± 0.13	Wood generalist
Buff Tip (Noctuidae)	*Phalera bucephala*	0.01 ± 0.01	Deciduous
Burnished Brass (Geometridae)	*Diachrysia chrysitis*	0.12 ± 0.04	Open ground
Chevron (Arctiidae)	*Eulithis testata*	0.01 ± 0.01	Open ground
Clouded Border (Noctuidae)	*Tyria jacobaeae*	0.11 ± 0.05	Deciduous
Clouded Bordered Brindle (Erebidae)	*Apamea crenata*	0.06 ± 0.03	Grassland
Clouded Buff (Geometridae)	*Diacrisia sannio*	0.02 ± 0.01	Moorland
Clouded Magpie (Geometridae)	*Abraxas sylvata*	0.04 ± 0.03	Grassland
Common Carpet (Erebidae)	*Epirrhoe alternata*	0.23 ± 0.06	Generalist
Common Footman (Drepanidae)	*Eilema lurideola*	0.01 ± 0.01	Generalist
Common Lute String (Geometridae)	*Ochropacha duplaris*	0.01 ± 0.01	Deciduous
Common Marbled Carpet (Noctuidae)	*Dysstroma truncata*	0.01 ± 0.01	Wood generalist
Common Rustic (Hepialidae)	*Mesapamea secalis*	0.11 ± 0.07	Generalist
Common Wainscot (Geometridae)	*Korscheltellus lupulina*	0.42 ± 0.22	Grassland
Common Wave (Geometridae)	*Cabera exanthemata*	0.8 ± 0.22	Deciduous
Coxcomb Prominent (Noctuidae)	*Cabera pusaria*	0.07 ± 0.03	Deciduous
Dark Arches (Geometridae)	*Apamea monoglypha*	0.27 ± 0.09	Generalist
Dark Brocade (Geometridae)[a]	*Xanthorhoe ferrugata*	0.17 ± 0.10	Generalist
Dark Marbled Carpet (Noctuidae)	*Dysstroma citrata*	0.54 ± 0.14	Generalist
Dark Tussock (Noctuidae)	*Abrostola triplasia*	0.01 ± 0.01	Open ground
Dotted Carpet (Noctuidae)	*Aporophyla lutulenta*	0.01 ± 0.01	Wood generalist

Dotted Clay (Noctuidae)	*Xestia baja*	0.22 ± 0.10	Generalist
Double Dart (Noctuidae)[a]	*Graphiphora augur*	0.02 ± 0.01	Wood generalist
Double Square Spot (Geometridae)	*Xestia triangulum*	0.27 ± 0.13	Deciduous
Double Striped Pug (Lasiocampidae)	*Gymnoscelis rufifasciata*	0.04 ± 0.02	Generalist
Drinker Moth (Noctuidae)	*Euthrix potatoria*	0.36 ± 0.09	Generalist
Dusky Brocade (Noctuidae)[a]	*Apamea remissa*	0.02 ± 0.02	Generalist
Dwarf Pug (Geometridae)	*Eupithecia tantillaria*	0.02 ± 0.01	Conifer
Ear Moth (Geometridae)[a]	*Amphipoea oculea*	0.08 ± 0.04	Generalist
Flame Carpet (Noctuidae)	*Selenia dentaria*	0.53 ± 0.14	Generalist
Flame Shoulder (Noctuidae)	*Ochropleura plecta*	0.58 ± 0.14	Generalist
Four Dotted Footman (Geometridae)	*Luperina testacea*	0.1 ± 0.05	Generalist
Foxglove Pug (Geometridae)	*Eupithecia pulchellata*	0.01 ± 0.01	Generalist
Frosted Orange (Noctuidae)	*Gortyna flavago*	0.01 ± 0.01	Generalist
Garden Carpet (Geometridae)	*Xanthorhoe fluctata*	0.13 ± 0.10	Generalist
Garden Tiger (Erebidae)[a]	*Arctia caja*	0.33 ± 0.12	Generalist
Gold Spangle (Noctuidae)	*Autographa bractea*	0.01 ± 0.01	Generalist
Gold Swift (Hepialidae)	*Phymatopus hecta*	0.02 ± 0.02	Generalist
Golden Rod Pug (Geometridae)	*Eupitheca virgaureata*	0.02 ± 0.01	Generalist
Golden Y (Noctuidae)	*Autographa jota*	0.09 ± 0.04	Generalist
Gothic (Noctuidae)	*Naenia typica*	0.01 ± 0.01	Deciduous
Green Arches (Noctuidae)	*Anaplectoides prasina*	0.01 ± 0.01	Generalist
Green Carpet (Geometridae)	*Colostygia pectinataria*	4.44 ± 0.86	Deciduous
Green Pug (Geometridae)	*Pasiphila rectangulata*	0.01 ± 0.01	Deciduous
Grey Arches (Noctuidae)	*Polia nebulosa*	0.01 ± 0.01	Generalist
Grey Dagger (Noctuidae)[a]	*Acronicta psi*	0.01 ± 0.01	Deciduous
Grey Mountain Carpet (Geometridae)[a]	*Entephria caesiata*	0.13 ± 0.05	Generalist
Grey Pine (Geometridae)	*Thera obeliscata*	0.03 ± 0.03	Moorland
Haworths Minor (Noctuidae)[a]	*Celaena haworthii*	0.18 ± 0.08	Conifer
Heath Rustic (Noctuidae)[a]	*Xestia agathina*	0.15 ± 0.13	Moorland
Ingrailed Clay (Noctuidae)	*Diarsia mendica*	2.36 ± 0.50	Open ground
July Highflyer (Geometridae)	*Hydriomena furcata*	1.54 ± 0.44	Generalist
Knotgrass (Noctuidae)[a]	*Acronicta rumicis*	0.03 ± 0.01	Wood generalist
Larch Pug (Geometridae)	*Eupithecia lariciata*	0.05 ± 0.03	Conifer
Large Emerald (Geometridae)	*Geometra papilionaria*	0.09 ± 0.04	Generalist
Large Yellow Underwing (Noctuidae)	*Noctua pronuba*	1.66 ± 1.01	Generalist
Latticed Heath (Geometridae)[a]	*Chiasmia clathrata*	0.01 ± 0.01	Generalist
Lempkes Gold Spot (Noctuidae)	*Plusia putnami*	0.14 ± 0.05	Generalist
Lesser Swallow Prominent (Notodontidae)	*Pheosia gnoma*	0.01 ± 0.01	Open ground
Lesser Yellow Underwing (Noctuidae)	*Noctua comes*	0.36 ± 0.15	Generalist
Light Emerald (Geometridae)	*Campaea margaritaria*	0.15 ± 0.07	Generalist
Map Winged Swift (Hepialidae)	*Korscheltellus fusconebulosa*	2.09 ± 0.39	Wood generalist
Marbled Minor (Noctuidae)	*Oligia strigilis*	0.11 ± 0.06	Generalist
Middle Barred Minor (Noctuidae)	*Oligia fasciuncula*	0.39 ± 0.14	Generalist
Mouse Moth (Noctuidae)[a]	*Amphipyra tragopoginis*	0.01 ± 0.01	Generalist

Muslin Footman (Arctiidae)	*Nudaria mundana*	0.09 ± 0.03	generalist
Narrow Winged Pug (Geometridae)	*Eupithecia nanata*	0.21 ± 0.09	Generalist
Neglected Rustic (Noctuidae)[a]	*Xestia castanea*	0.04 ± 0.02	Open ground
Northern Arches (Noctuidae)	*Apamea exulis*	0.91 ± 0.31	Open ground
Northern Spinach (Geometridae)	*Eulithis populata*	0.01 ± 0.01	Open ground
Pale Eggar (Lasiocampidae)[a]	*Trichiura crataegi*	0.02 ± 0.01	Generalist
Peach Blossom (Drepanidae)	*Thyatira batis*	0.04 ± 0.02	Generalist
Pebble Prominent (Notodontidae)	*Notodonta ziczac*	0.05 ± 0.02	Deciduous
Pine Carpet (Geometridae)	*Pennithera firmata*	0.01 ± 0.01	Deciduous
Pink Barred Sallow (Noctuidae)	*Xanthia togata*	0.04 ± 0.02	Conifer
Poplar Grey (Noctuidae)	*Subacronicta megacephala*	0.02 ± 0.01	Generalist
Poplar Hawk Moth (Sphingidae)	*Laothoe populi*	0.01 ± 0.01	Deciduous
Pretty Pinion (Geometridae)	*Perizoma blandiata*	0.29 ± 0.07	Generalist
Purple Bar (Geometridae)	*Cosmorhoe ocellata*	0.56 ± 0.15	Moorland
Purple Clay (Noctuidae)	*Diarsia brunnea*	0.09 ± 0.03	Open ground
Red Carpet (Geometridae)[a]	*Xanthorhoe decoloraria*	0.01 ± 0.01	Generalist
Red Twin Spot Carpet (Geometridae)	*Xanthorhoe spadicearia*	0.01 ± 0.01	Generalist
Riband Wave (Geometridae)	*Idaea aversata*	0.01 ± 0.01	Moorland
Rosy Minor (Noctuidae)	*Litoligia literosa*	0.01 ± 0.01	Generalist
Rustic (Noctuidae)[a]	*Hoplodrina blanda*	0.01 ± 0.01	Grassland
Sallow (Noctuidae)[a]	*Cirrhia icteritia*	0.01 ± 0.01	Generalist
Satyr Pug (Geometridae)	*Eupithecia satyrata*	0.01 ± 0.01	Moorland
Saxon (Noctuidae)	*Hyppa rectilinea*	0.28 ± 0.14	Generalist
Scalloped Hazel (Geometridae)	*Odontopera bidentata*	0.01 ± 0.01	Generalist
Scalloped Hooktip (Drepanidae)	*Falcaria lacertinaria*	0.04 ± 0.02	Wood generalist
Scalloped Oak (Geometridae)	*Crocallis elinguaria*	0.01 ± 0.01	Generalist
Scalloped Shell (Geometridae)	*Hydria undulata*	0.08 ± 0.04	Wood generalist
Scarce Silver Y (Noctuidae)	*Syngrapha interrogationis*	1.25 ± 0.43	Deciduous
Shoulder Striped Wainscot (Noctuidae)[a]	*Leucania comma*	0.01 ± 0.01	Moorland
Silver Ground Carpet (Geometridae)	*Xanthorhoe montanata*	0.01 ± 0.01	Generalist
Sixstriped Rustic (Noctuidae)	*Xestia sexstrigata*	0.17 ± 0.04	Generalist
Small Angleshades (Noctuidae)	*Euplexia lucipara*	0.01 ± 0.01	Generalist
Small Dotted Buff (Noctuidae)	*Photedes minima*	0.07 ± 0.03	Generalist
Small Fanfoot (Erebidae)	*Herminia grisealis*	0.09 ± 0.04	Generalist
Small Phoenix (Geometridae)[a]	*Ecliptopera silaceata*	0.07 ± 0.02	Deciduous
Small Rivulet (Geometridae)	*Perizoma alchemillata*	0.01 ± 0.01	Generalist
Small Square Spot (Noctuidae)[a]	*Diarsia rubi*	0.07 ± 0.04	Generalist
Small Wainscot (Noctuidae)	*Denticucullus pygmina*	0.21 ± 0.14	Generalist
Smokey Wainscot (Noctuidae)	*Mythimna impura*	0.01 ± 0.01	Generalist
Snout (Erebidae)	*Hypena proboscidalis*	0.08 ± 0.04	Generalist
Spruce Carpet (Geometridae)	*Thera britannica*	0.01 ± 0.01	Generalist
Square Spot Rustic (Noctuidae)	*Xestia xanthographa*	0.05 ± 0.03	Conifer
Square Spotted Clay (Noctuidae)	*Xestia stigmatica*	0.22 ± 0.10	Generalist
Straw Dot (Noctuidae)	*Rivula sericealis*	0.22 ± 0.11	Deciduous
Striped Twin Spot Carpet (Geometridae)	*Coenotephria salicata*	0.01 ± 0.01	Open ground

Swallow Prominent (Notodontidae)	*Pheosia tremula*	0.34 ± 0.10	Generalist
Tawny Barred Angle (Geometridae)	*Macaria liturata*	0.01 ± 0.01	Deciduous
The Clay (Noctuidae)	*Mythimna ferrago*	0.02 ± 0.02	Conifer
Treble Bar (Geometridae)	*Aplocera plagiata*	0.01 ± 0.01	Open ground
Triple Spotted Clay (Noctuidae)	*Xestia ditrapezium*	4.09 ± 0.82	Generalist
True Lovers Knot (Noctuidae)	*Lycophotia porphyrea*	0.07 ± 0.07	Deciduous
Twin Spot Carpet (Geometridae)	*Mesotype didymata*	0.01 ± 0.01	Moorland
Water Carpet (Geometridae)	*Lampropteryx suffumata*	0.04 ± 0.02	Open ground
Welsh Wave (Geometridae)	*Venusia cambrica*	0.05 ± 0.02	Generalist
White Ermine (Erebidae)[a]	*Spilosoma lubricipeda*	0.02 ± 0.01	Generalist
White Wave (Geometridae)	*Cabera pusaria*	4.07 ± 1.03	Generalist
Willow Beauty (Geometridae)	*Peribatodes rhomboidaria*	0.05 ± 0.03	Wood generalist
Wormwood Pug (Geometridae)	*Eupithecia absinthiata*	0.01 ± 0.01	Generalist

Table 2: List of micro moth species recorded:

Common name (Family)	Latin Name	Habitat preference	Abundance per trap (± SE)
Water Veneer (Crambidae)	*Acentria ephemerella*	Water	0.05 ± 0.03
Caledonian Button (Tortricidae)	*Acleris caledoniana*	Moorland	0.01 ± 0.01
Notched winged Tortricid (Tortricidae)	*Acleris emargana*	Deciduous	0.04 ± 0.02
Dark-triangle Buttion (Tortricidae)	*Acleris laterana*	Open ground	0.01 ± 0.01
Rhomboid Tortrix (Tortricidae)	*Acleris rhombana*	Generalist	0.01 ± 0.01
Thistle Conch (Tortricidae)	*Aethes cnicana*	Grassland	0.04 ± 0.03
Burdock Conch (Tortricidae)	*Aethes rubigana*	Open ground	0.01 ± 0.01
Hook-marked Straw Moth (Tortricidae)	*Agapeta hamana*	Open ground	0.01 ± 0.01
Hemlock Moth (Depressariidae)	*Agonopterix alstromeriana*	Open ground	0.01 ± 0.01
Angelica Flat-body (Depressariidae)	*Agonopterix angelicella*	Generalist	0.01 ± 0.01
Brindled Flat-body (Depressariidae)	*Agonopterix arenella*	Generalist	0.01 ± 0.01
Gorse Tip Moth (Depressariidae)	*Agonopterix nervosa*	Generalist	0.02 ± 0.01
Coastal Flat-body (Depressariidae)	*Agonopterix yeatiana*	Generalist	0.01 ± 0.01
Barred Grass Veneer (Crambidae)	*Agriphila inquinatella*	Grassland	0.02 ± 0.01
Pearl Veneer (Crambidae)	*Agriphila straminella*	Grassland	0.68 ± 0.18
Common Grass Veneer (Crambidae)	*Agriphila tristella*	Grassland	0.01 ± 0.01
Broken Barred Roller (Tortricidae)	*Ancylis unguicella*	Moorland	0.01 ± 0.01
Birch Marble (Tortricidae)	*Apotomis betuletana*	Deciduous	0.05 ± 0.03
Rush Marble (Tortricidae)	*Bactra lancealana*	Open ground	0.22 ± 0.07
(Blastobasidae)	*Blastobasis decolorella*	Wood generalist	0.01 ± 0.01
Dark Groundling (Gelechiidae)	*Bryotropha affinis*	Generalist	0.01 ± 0.01
(Gelechiidae)	*Bryotropha boreella*	Generalist	0.01 ± 0.01
Cinereous Groundling (Gelechiidae)	*Bryotropha terrella*	Grassland	0.01 ± 0.01
Pearl-band Grass Veneer (Crambidae)	*Catoptria margaritella*	Moorland	0.21 ± 0.10
Pearl Grass Veneer (Crambidae)	*Catoptria pinella*	Moorland	0.01 ± 0.01
Dark Strawberry Tortrix (Tortricidae)	*Celypha lacunana*	Generalist	1.23 ± 0.30
Garden Grass Veneer (Crambidae)	*Chrystoteuchia culmella*	Grassland	0.14 ± 0.06
Flax Tortrix (Tortricidae)	*Cnephasia asseclana*	Generalist	0.01 ± 0.01
Hedge Case-bearer (Coleophoridae)	*Coleophora striatipennella*	Deciduous	0.01 ± 0.01
Hook-streaked Grass Veneer (Crambidae)	*Crambus lathoniellus*	Grassland	0.01 ± 0.01
Grass Veneer (Crambidae)	*Crambus pascuella*	Grassland	0.31 ± 0.09
Grey Gorse Piercer (Tortricidae)	*Cydia ulicetana*	Open ground	0.23 ± 0.07
Northern Tubic (Oecophoridae)	*Denisia similella*	Deciduous	0.01 ± 0.01
Little Grey (Crambidae)	*Dipleurina lacustrata*	Deciduous	0.01 ± 0.01
(Crambidae)	*Donacaula micronellus*	Moorland	0.04 ± 0.02
Dotted Shade (Tortricidae)	*Eana osseana*	Open ground	0.01 ± 0.01
Brown China Mark (Crambidae)	*Elophila nymphaeata*	Water	0.01 ± 0.01
Knapweed Bell (Tortricidae)	*Epiblema cirsiana*	Deciduous	0.01 ± 0.01
Thistle Bell (Tortricidae)	*Epiblema scutulana*	Open ground	0.01 ± 0.01

Bramble Shoot Moth (Tortricidae)	*Epiblema uddmanniana*	Deciduous	0.01 ± 0.01
Square Barred Bell (Tortricidae)	*Epinotia fraternella*	Conifer	0.01 ± 0.01
Common Birch Bell (Tortricidae)	*Epinotia immundana*	Deciduous	0.16 ± 0.09
Grey Poplar Bell (Tortricidae)	*Epinotia nisella*	Deciduous	0.03 ± 0.03
Small Birch Bell (Tortricidae)	*Epinotia ramella*	Deciduous	0.01 ± 0.01
Variable Bell (Tortricidae)	*Epinotia solandriana*	Deciduous	0.01 ± 0.01
Common Spruce Bell (Tortricidae)	*Epinotia tedella*	Conifer	0.01 ± 0.01
White Blotch Bell (Tortricidae)	*Epinotia trigonella*	Wood generalist	0.11 ± 0.04
Bright Bell (Tortricidae)	*Eucosma hohenwartiana*	Grassland	0.02 ± 0.02
Two-coloured Bell (Tortricidae)	*Eucosma obumbratana*	Open ground	0.04 ± 0.02
Pied Grey (Crambidae)	*Eudonia delunella*	Deciduous	0.01 ± 0.01
Small Grey (Crambidae)	*Eudonia mercurella*	Deciduous	0.01 ± 0.01
Brassy Tortrix (Tortricidae)	*Eulia ministrana*	Deciduous	0.25 ± 0.16
Lilac Leafminer (Gracillariidae)	*Gracillaria syringella*	Generalist	0.01 ± 0.01
Small Fanfoot (Erebidae)	*Herminia grisealis*	Deciduous	0.02 ± 0.01
Marsh Oblique-barred (Erebidae)	*Hypenodes humidalis*	Open ground	0.99 ± 0.44
Red Piercer (Tortricidae)	*Lathronympha strigana*	Wood generalist	0.01 ± 0.01
Rust-blotch Cosmet (Momphidae)	*Mompha lacteella*	Grassland	0.01 ± 0.01
Little Cosmet (Momphidae)	*Mompha raschkiella*	Grassland	0.01 ± 0.01
Carrion Moth (tineidae)	*Monopis weaverella*	Generalist	0.01 ± 0.01
Heather Groundling (Gelechiidae)	*Neofaculta ericetella*	Moorland	0.01 ± 0.01
Beautiful China Mark (Crambidae)	*Nymphula stagnata*	Water	0.08 ± 0.03
Sorrel Bent-wing (Opostegidae)	*Opostega salaciella*	Grassland	0.01 ± 0.01
Woodland Marble (Tortricidae)	*Orthotaenia undulana*	Generalist	0.01 ± 0.01
Barred Fruit Tree Tortrix (Tortricidae)	*Pandemis cerasana*	Deciduous	0.04 ± 0.03
White-faced Tortrix (Tortricidae)	*Pandemis cinnamomeana*	Deciduous	0.01 ± 0.01
Dark Fruit Tree Tortrix (Tortricidae)	*Pandemis heparana*	Deciduous	0.03 ± 0.01
Large Marble (Tortricidae)	*Phiaris schulziana*	Moorland	0.01 ± 0.01
Small Clouded Knot-horn (Pyralidae)	*Phycitodes saxicola*	Open ground	0.01 ± 0.01
Light Streak (Oecophoridae)	*Pleurota bicostella*	Moorland	0.01 ± 0.01
Diamondback Moth (Plutellidae)	*Plutella xylostella*	Generalist	0.01 ± 0.01
Ash Bud Moth (Praydicae)	*Prays fraxinella*	Deciduous	0.01 ± 0.01
White Plume Moth (Pterophoridae)	*Pterophorus pentadactyla*	Generalist	0.01 ± 0.01
Common Purple and Gold (Crambidae)	*Pyrausta purpuralis*	Grassland	0.01 ± 0.01
Holly Tortrix Moth (Tortricidae)	*Rhopobota naevana*	Generalist	0.04 ± 0.02
Pinion Streaked Snout (Hypenodinae)	*Schrankia costaestrigalis*	Open ground	0.57 ± 0.15
Common Grey (Crambidae)	*Scoparia ambigualis*	Deciduous	3.26 ± 0.62
Meadow Grey (Crambidae)	*Scoparia pyralella*	Open ground	0.05 ± 0.02
Brown Plume (Pterophoridae)	*Stenoptilia pterodactyla*	Generalist	0.01 ± 0.01
Fulvous Clothes Moth (tineidae)	*Tinea semifulvella*	Generalist	0.01 ± 0.01
Birds-nest Moth (tineidae)	*Tinea trinotella*	Generalist	0.01 ± 0.01
Pale Straw Pearl (Crambidae)	*Udea lutealis*	Generalist	0.17 ± 0.07
Olive Pearl (Crambidae)	*Udea olivalis*	Generalist	0.02 ± 0.01
Dusky Pearl (Crambidae)	*Udea prunalis*	Generalist	0.01 ± 0.01
Spindle Ermine (Yponomeutidae)	*Yponomeuta cagnagella*	Deciduous	0.01 ± 0.01
Bird-cherry Ermine (Yponomeutidae)	*Yponomeuta evonymella*	Deciduous	0.44 ± 0.43

White-shouldered Smudge (Ypsolophidae)	*Ypsolopha parenthesella*	Deciduous	0.01 ± 0.01
Larch Tortrix (Tortricidae)	*Zeiraphera griseana*	Conifer	0.15 ± 0.12
Spruce Bud Moth (Tortricidae)	*Zeiraphera ratzeburgiana*	Conifer	0.17 ± 0.06

Supplementary data 4:

Stand characteristics for each management stage and stand features associated with management.

*Diameter at Breast Height – estimate of tree maturity

Stand Age	Management Stage	Key stand features
40 – 60 years	Mature	Occasionally thinned, stand density between 500 and 2200 stems ha^{-1}, average stand density: 1267 stems ha^{-1}, canopy closure between 80 and 100%, average closure 99%
20 – 40 years	Thin	Trees more densely packed, losing midstem branches and some trees dying off (self thinned). Occasionally thinned through management. Stand density between 600 – 2800 stems ha^{-1}, average stand density: 1624 stems ha^{-1}. Canopy closure between 50 and 100%, average closure: 95%
10 – 20 years	Thicket	Very dense, retain midstem branches, no undergrowth. Stand density between 300 – 3000 stems ha^{-1}, average stand density: 1850 stems ha^{-1}. Canopy closure between 16 and 100%, average closure: 69%
5 – 10 years	Young	Small, nearly all trees < 7cm DBH*, no canopy closure, lots of vegetation and ground cover
Clearfell	Felled < 5 years ago	Lots of dead wood and brash, standing water and undergrowth
Native	Unmanaged	Broadleaf stand, planted as part of plantation restructuring