1 **Title page**

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3 Title: Evaluating the effects of integrating trees into temperate arable systems on pest control

4 and pollination

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Abstract

Agroforestry systems, which incorporate trees into agricultural land, could contribute to sustainable agricultural intensification as they have been shown to increase land productivity, biodiversity and some regulating ecosystem services. However, the effect of temperate agroforestry systems on pest control and pollination services has not been comprehensively reviewed, despite the importance of these services for sustainable intensification. We review and analyse the available evidence for silvoarable agroforestry systems, following which we propose a predictive framework for future research to explain the observed variation in results, based on ecological theory and evidence from analogous systems. Of the 12 studies included in our meta-analysis of natural enemies and pests, the observed increases in natural enemy abundance (+24%) and decreases in arthropod herbivore/pest abundance (-25%) in silvoarable systems were both significant, but molluscan pests were more abundant in silvoarable systems in the two available studies. Only three studies reported effects on pollinators, but all found higher abundance in silvoarable compared with arable systems. Measures of pest control or pollination service are scarce, but suggest stronger effect sizes. Our framework seeks to establish hypotheses for future research through an interpretation of our findings in the context of the wider literature, including landscape characteristics, silvoarable system design and management, system maturity, trophic interactions and experimental design. Our findings suggest that silvoarable systems can contribute to sustainable intensification by enhancing beneficial invertebrates and suppressing arthropod pests compared with arable, but future research should include measures of pest control and pollination and implications for productivity and economic value.

Keywords: Agroforestry; Alley cropping; Sustainable agriculture; Conservation biological control; Pollinators; Natural enemies

1 Introduction

Global crop demand is rising rapidly, and is forecasted to increase by 100-110% from 2005 to 2050 (Tilman et al., 2011). The intensification of arable production in temperate regions has driven declines in biodiversity and associated ecosystem services, such as pest control and pollination (Bartomeus et al., 2014; Bianchi et al., 2006). This has in many cases led to a reliance on management techniques such as pesticide application, genetically modified crops and maintenance of managed honey bee colonies. The sustainability of such management practices is threatened by processes such as pesticide resistance (Sparks and Nauen, 2015), secondary pest outbreaks (Dutcher, 2007; Hill et al., 2017), depletion of non-renewable sources, environmental and human health risks associated with pesticides (Bernardes et al., 2015; Kim et al., 2017), and honey bee colony collapse or growth deficits (Aizen and Harder, 2009; Neumann and Carreck, 2010).

There is a strong and growing pressure to move towards more sustainable intensification of production, through harnessing natural processes to sustain productivity rather than relying on pesticides and managed pollinators (FAO, 2013; Power, 2010). One alternative tactic for reducing crop damage by pests is to enhance the effectiveness of their natural enemies, such as predators and parasitoids, by enhancing plant diversity and habitat complexity (Begg et al., 2017). This is the principle of conservation biological control (Barbosa, 1998). Similar arguments have been proposed to encourage wild pollinators (Kovács-Hostyánszki et al., 2017; Woodcock et al., 2016), which have the potential to increase the effectiveness of pollination in flowering crops and mitigate against potential honey bee losses (Garibaldi et al., 2013; Hoehn et al., 2008).

One possible solution to the need for sustainable intensification is agroforestry, essentially 'the incorporation of trees into farming systems' (Gordon et al., 2018). Agroforestry has been proposed as a 'win-win' opportunity for productivity and environmental protection (The Woodland Trust, 2018). Although more typical of the tropics due to lower constraints posed

71   by mechanisation and climatic factors such as light availability, there is growing interest in this

72   land use system in temperate regions because of its potential contribution towards sustainable

73   intensification (Newman and Gordon, 2018; Smith et al., 2012). For example, the

74   'establishment, regeneration or renovation of agroforestry systems' is promoted through the

75   European Union's Common Agricultural Policy. Agroforestry is perceived as being beneficial

76   for the environment and land stewardship, which are typically the main drivers for adoption

77   (García de Jalón et al., 2018; Matthews et al., 1993).

78   Of particular interest in terms of the potential benefit from natural pest control and pollination

79   is silvoarable agroforestry, which is the intercropping of trees or shrubs with arable crops (Fig.

80   1). Different methods of silvoarable production are practiced throughout northern temperate

81   regions, sometimes being referred to by regional terminologies. These include tree-based

82   intercropping and alley cropping systems in North America which typically use hardwoods for

83   nut and timber production, and various agri-silviculture systems in the Himalayas (Newman

84   and Gordon, 2018). Timber is typically the main tree product produced in silvoarable systems,

85   although intercropping with fruit trees is widely practised in China (Chang et al., 2018) and its

86   potential for a quick return on investment is encouraging uptake in the UK (Newman et al.,

87   2018). Silvoarable systems are far scarcer in southern temperate regions, although research

88   platforms have been established (Newman and Gordon, 2018). Temperate silvoarable

89   systems have the potential to increase productivity compared with equivalent monocropped

90   land, for example Land Equivalent Ratios of between 0.98 and 1.37 have been estimated over

91   the full tree rotation (Graves et al., 2010; Gruenewald et al., 2007).

92   Several reviews and meta-analyses have demonstrated that temperate agroforestry systems

93   generally enhance biodiversity and some ecosystem services compared with arable cropping

94   (Smith et al., 2013; Stamps and Linit, 1997; Torralba et al., 2016; Tsonkova et al., 2012).

95   However, the effects of silvoarable systems on pest control and pollination services remain

96   poorly understood in temperate regions; all but two of 42 studies included in a recent meta-

97   analysis of pest, disease and weed control were conducted in the tropics and sub-tropics,

4

98 which typically have different mechanisation requirements and utilise different tree/crop

99 combinations to those used in temperate regions (Pumariño et al., 2015).

100
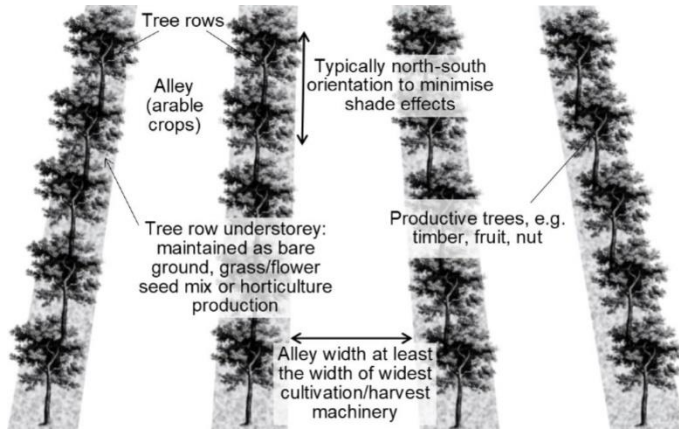
102 **Fig. 1.** Illustration of a typical silvoarable alley-cropping system.

103 The aims of this review are: 1) to collate and analyse studies of pollinators, pests and their

104 natural enemies in temperate silvoarable systems, specifically in terms of their potential

105 contribution to pest control and pollination ecosystem services; and 2) to develop a framework

106 for future research to predict the factors which influence variation in results, with the aspiration

107 of driving forward a unified research agenda.

108

2   Methods

110 Literature was sourced based on the following criteria (the selection process is summarised

111 at Supplementary Material 1):

112   1. A measure of abundance or activity density of invertebrate herbivores/pests, natural

113   enemies or pollinators, and/or a measure of conservation biological control of animal

114   pests and/or pollination were recorded;

115   2. Studies were undertaken in a temperate region, defined as latitude greater than 40º

116   north or south;

117   3. A silvoarable system, for this purpose defined as trees or shrubs incorporated into an

118   arable field, was compared with an arable control, with the respective arable

119   components comprising annual crops.

120 To minimise the risk of publication bias, we sourced both peer-reviewed and non-peer-

121 reviewed literature, including theses and reports.

122 ***2.1 Data extraction***

123 A total of 19 datasets were identified (Supplementary Materials 2 and 3). We reviewed the

124 characteristics of each study and the studied system(s), including sampling duration, alley

125 width, system age, number of taxonomic orders studied and minimum distance between

126 silvoarable and arable control plots. Capture or abundance data for natural enemies, pests (or

127 herbivores where pest species were not specified), pollinators, and pest control proxies was

128 sourced from each dataset to analyse effect sizes. Where necessary, data was extracted from

129 figures using GetData Graph Digitizer (version 2.26, http://getdata-graph-digitizer.com). Any

130 data collected from tree rows was excluded where possible to provide a comparison of

131 silvoarable alleys versus arable. Where pitfall trap data from tree rows could not be excluded,

132 the study/site was omitted entirely from the analysis of effect sizes, because the structural

133 complexity of vegetation in tree rows could reduce capture rates (Melbourne, 1999; Thomas

134 et al., 2006). One study was completely excluded and one study partially excluded (two of the

135 three sites) on this basis (Supplementary Material 3).

136 ***2.2 Meta-analysis for herbivores/pests and natural enemies***

137 To quantify the magnitude of effects for herbivores/pests and natural enemies, we calculated

138 effect size as the log response ratio (Hedges et al., 1999) of mean functional group abundance

139 in the silvoarable system versus the arable control. Hence, the response variables were

140 herbivore/pest abundance and natural enemy abundance. The single explanatory variable

141 was presence or absence of a silvoarable system.

142   Standard deviations could not be extracted for four of the 12 identified studies (Supplementary

143   Material 3), so were imputed based on their mean values (Lajeunesse, 2013). Three of the

144   four studies with missing standard deviations used pitfall trapping, therefore imputed standard

145   deviations were calculated based on the significant linear relationship between mean and

146   standard deviation for the two available pitfall trap studies with standard deviation data

147   (Griffiths et al., 1998; Phillips et al., 1994). The significance of effects for herbivore/pest and

148   natural enemy abundances were analysed in a mixed-effects meta-analysis model, using the

149   rma.mv function of the metaphor package version 2.1-0 (Viechtbauer, 2010) within R version

150   3.5.2 (R Core Team, 2018). As multiple data points were extracted from some individual

151   studies, study ID was included as a random effect. The results are reported as back-

152   transformed values.

153   The imputation of standard deviations did not increase the risk of Type 1 errors, as effect sizes

154   were reduced and p-values increased, compared with models which omitted studies with

155   missing standard deviations. Outliers and influential observations were quantified using

156   Cook's distance. For the pest/herbivores model, Cook's distance for a slug abundance data

157   point was 0.30, compared with less than 0.05 for all other data points. Therefore, the results

158   of a model excluding slug data (i.e. arthropods only) are also presented. For the natural

159   enemies model, the data-point with the highest Cook's distance (0.13) was a negative effect

160   size (i.e. lower abundance in the silvoarable plot than arable control) and was therefore

161   retained to reduce the likelihood of a Type 1 error. Cook's distance was below 0.10 for all other

162   data points. Publication bias was considered unlikely due to the inclusion of unpublished

163   studies, but funnel plots were visually checked for symmetry. Heterogeneity, in the form of I^2

164   calculated from the models without random effects, ranged from 56% to 75%, lower than the

165   median of 85% reported for ecological meta-analyses (Senior et al., 2016).

166   ### *2.3   Review of other effect sizes*

167   Effect sizes were calculated from five studies which reported a proxy for pest control, such as

168   ratios of natural enemies to herbivores, pest mortality rates or pest parasitism rates, in a

169 silvoarable system versus an arable control. Pollinator effect sizes were derived from three

170 studies which reported abundances in silvoarable systems and arable controls. To investigate

171 whether the functional group responses are highly influenced by any specific taxa, effect sizes

172 were also calculated for taxa which were included in three or more studies (Araneae,

173 Carabidae, Coccinellidae, Syrphidae and Aphididae). We calculated effect size as the mean

174 abundance (or for pest control proxies, the mortality/parasitism rate or ratio of natural enemies

175 to pests) in the silvoarable system, divided by the respective value for the arable control. Due

176 to the low number of available studies for these measures, pooled effect sizes were not

177 analysed. Finally, four studies reported some measure of crop damage or yield, which we

178 describe in the Results.

179 ### *2.4   Predictive framework*

180 Our findings were used to inform and construct a predictive framework for future research,

181 which identifies a series of hypotheses to predict the factors which influence variation in the

182 results. The components of the framework were selected based on a wider review of

183 ecological theory and analogous systems, such as hedgerows, field margins, flower strips and
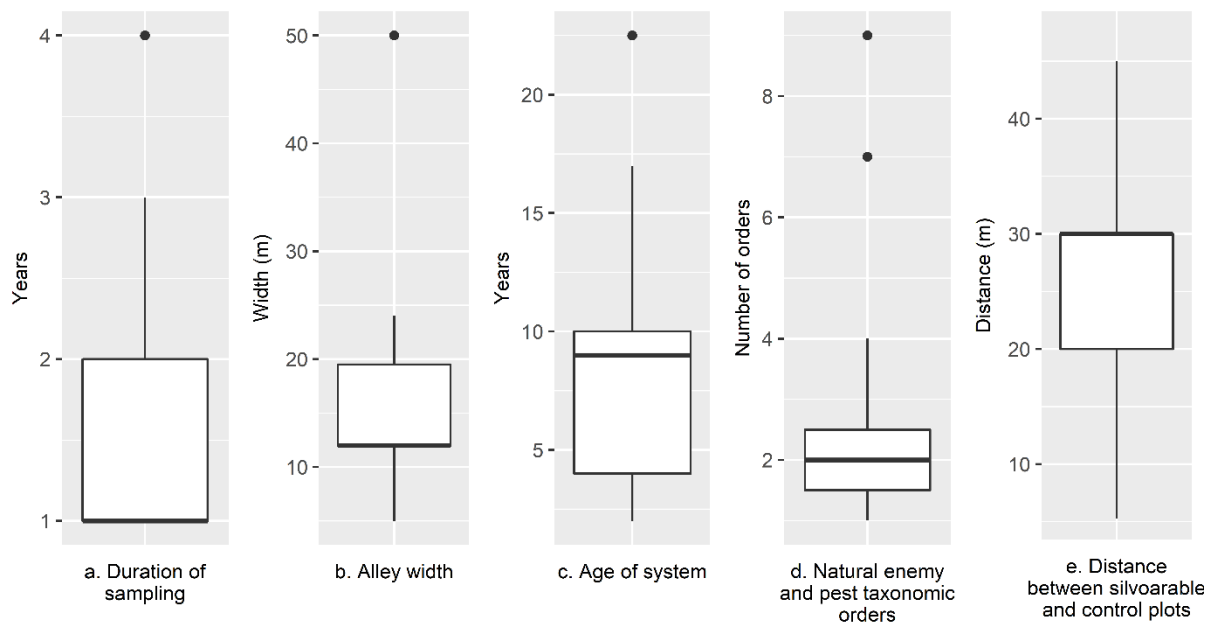
184 beetle banks.

185

186 ## 3   Results

187 ### *3.1   Characteristics of studies*

188 A total of 19 datasets were extracted from 17 studies undertaken in five countries, comprising

189 Canada, France, Turkey, UK and USA, with publication dates ranging from 1993 to 2015

190 (Supplementary Material 2). Data from the majority of the studies included in our analysis were

191 taken from single sites over less than two years (Fig. 2a). There was a strong bias towards

192 systems with alley widths of around 12 m (Fig. 2b). Most of the studied systems were relatively

193 young in age, i.e. less than ten years since planting (Fig 2c). The majority of studies report on

194   the abundances of three or fewer taxonomic orders, with only two studies reporting on seven

195   or more orders (Fig. 2d). Where the minimum distance between the silvoarable and arable

196   plots is specified, this is typically less than 50 m (Fig 2e, three outliers are not shown).

197

a. Duration of sampling   b. Alley width   c. Age of system   d. Natural enemy and pest taxonomic orders   e. Distance between silvoarable and control plots

198

199   **Fig. 2.** Characteristics of studies of invertebrate pest control and pollination in temperate silvoarable

200   systems, where the relevant information is specified (Supplementary Material 2). For studies of multiple

201   sites, each site is represented individually. Multiple studies reporting on the same data are represented

202   once collectively. Each 'box' represents the first and third quartiles, whilst the 'whiskers' extend to the

203   largest/smallest value no further than 1.5 * inter-quartile range from the box. Three outliers are not

204   plotted in Fig. 2e (130 m, 210 m and 270 m), but are included in the calculations.

3.2   *Herbivores/pests and natural enemies: meta-analysis*

206   Invertebrate herbivore/pest abundances were lower in the silvoarable compared with arable

207   systems, with a back-transformed mean effect size of 0.89 (Fig. 3), but this was not significant

208   ($z=-0.650$, p-value=0.516). However, the abundance of arthropod herbivores/pests was

209   significantly lower in the silvoarable than arable systems ($z=-2.005$, p-value=0.045), with a

210   mean effect size of 0.75 (Fig. 3). This contrasts to slug abundance, which was higher in the

211   silvoarable than arable systems, with effect sizes of 1.12 to 1.53 across the two studies.

Natural enemy abundance was significantly higher in silvoarable compared with arable systems (z=2.528, p-value=0.011), with a mean effect size of 1.24 (Fig. 3). Only one of the nine natural enemy effect sizes were less than one (Supplementary Material 3).
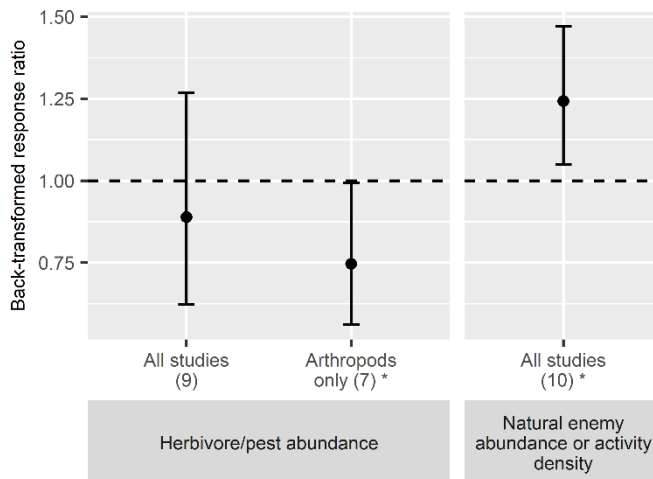
Fig. 3. Means and confidence intervals of the back-transformed response ratios of invertebrate herbivore/pest and natural enemy abundance in silvoarable alleys (treatment) versus arable fields (control). A response ratio of greater than 1 indicates a higher abundance in the silvoarable than the arable system. Numbers in parentheses represent the number of studies and '*' denotes significance (p-value < 0.05). Data is provided in Supplementary Material 3.

Data from four sites reported in two studies were not included in the effect size analysis because pitfall trap data from tree rows and alleys could not be separated. In these studies, natural enemy activity was lower in the silvoarable system than the arable control at three of the four sites, whilst the study which also sampled slugs found higher captures in the silvoarable than the arable system at one site but lower captures in the silvoarable system at the other site (Supplementary Material 3).

3.3 Proxies for pest control

One measure of pest control is the ratio of the number of natural enemies to herbivores/pests. Two studies found a higher ratio in silvoarable versus arable systems (Table 1), which could be seen as a proxy for higher pest control. Three datasets included mortality or parasitism

231 rates of pests, and all found consistently higher rates in silvoarable systems compared with

232 arable systems (Table 1), again suggesting a higher level of pest control.

233

234 **Table 1**

235 Summary of studies which reported proxies for pest control, i.e. ratios of airborne natural

236 enemies to herbivores or mortality/parasitism rates. Effect sizes are calculated as the

237 silvoarable ratio/rate divided by the respective arable control value.

Reference	Proxies for pest control	Silvoarable		Arable		Effect size	Tree row data excluded?
		Ratio	%	Ratio	%		
Peng et al. (1993)	Ratio of airborne natural enemies to herbivores	1.46	-	1.15	-	1.27	Yes
Howell (2001)	Ratio of airborne predators to herbivores	1.79	-	1.37	-	1.31	No
	Ratio of airborne parasitoids to herbivores	2.94	-	1.08	-	2.72	
Stamps et al. (2009a)	Alfalfa weevil mortality rate	-	33.85	-	28.26	1.20	Yes (not sampled)
Naeem et al. (1997); Naeem et al. (1994)	Aphid parasitism rate	-	2.81	-	1.66	1.69	Yes
Muhammad et al. (2005)	Aphid parasitism rate	-	12.8	-	7.6	1.68	Yes (not sampled)

238

239 *3.4 Pollinator abundance*

240 Only three studies, in the UK and Canada, reported abundances of pollinating insects in

241 silvoarable systems and arable controls. Effect sizes ranged from 1.17 to 2.55, indicating

242   beneficial effects on pollinator populations in silvoarable systems compared with arable

243   controls (Table 2), but study replication was low. One study also reported higher California

244   Poppy phytometer seedset by a factor of 4.5 in agroforestry compared with arable systems

245   (Table 2).

246

247   **Table 2**

248   Effect sizes for studies which reported pollinator abundances or pollination service, calculated

249   as pollinator abundance or seedset in the silvoarable system divided by the respective value

250   in the arable control.

Reference	Taxa / measure of service	Effect size	Tree row data excluded?
Peng et al. (1993)	Syrphidae, *Bombus*	1.17	Yes
Howell (2001)	Andrenidae, Apidae, Colletidae, Halictidae, Megachilidae,	1.72	No
Varah (2015): 2 sites	Syrphidae, *Bombus* (solitary bees excluded as silvoarable data not separable from silvopasture data)	2.55	No
	Seedset in *Eschscholtzia californica* phytometers (across two silvoarable and one silvopasture site, not separable)	4.5	No

251

252

253   *3.5 Taxon-specific effects*

254   The results were also analysed for aphids and four taxa of predators comprising Araneae,

255   Carabidae, Coccinellidae and Syrphidae. The effect sizes were highly variable, ranging below

256   and above 1 in four of the five taxa analysed (Table 3). The only taxon represented by at least

257   three studies which had consistently higher numbers in silvoarable systems compared with

258 arable controls was hoverflies (Syrphidae).

259

260 **Table 3**

261 Effect sizes for five of the most commonly studied taxa in temperate silvoarable systems,

262 calculated as total or mean abundance in the silvoarable system divided by the respective

263 value in the arable control. Syrphidae only include species with predatory larvae.

Reference	Effect size				
	Natural enemies				Herbivores / pests
	Araneae	Carabidae	Coccinellidae	Syrphidae	Aphidoidea
Peng et al. (1993)	1.35 (airborne)	-	0.25	1.22	1.77 (all species)
Phillips et al. (1994)	-	0.83	-	2.64	-
Peng and Sutton (1996)	1.22	1.12	3.2	-	
Naeem et al. (1994, 1997)	-	-	-	-	0.53 (one species)
Howell (2001)	0.95 (airborne)	9 (airborne)	0.5	1.51	0.26 (all species)
Burgess et al. (2003): Leeds site	0.65	0.73	-	-	-
Muhammad et al. (2005)	-	-	-	-	0.45 (one species)
Smits et al. (2012)	-	-	-	-	1.01 (three species)
Sharman (2015)	-	1.54	-	-	-

264

265 *3.6   Implications for crop damage and yield*

266 Evidence of crop damage by invertebrate pests is very limited, and only two studies have

267 attempted to establish a link between pest control and yield of the arable component. Griffiths

268 et al. (1998) recorded higher slug damage to a pea crop in a UK silvoarable system compared

269   with an arable control, with damage level positively correlated to slug captures. However, yield

270   was not measured. In Turkey, Akbulut et al. (2003) observed a lower level of crop damage

271   from invertebrates in silvoarable plots, accompanied by higher yield of beans but lower yield

272   of maize, relative to arable. Other studies have simultaneously sampled cereal yields and

273   invertebrates in silvoarable systems, finding lower silvoarable yields compared with arable in

274   conventional systems (Burgess et al., 2003), and the opposite result in organic systems

275   (Varah, 2015), but disentangling the effect of pest control or pollination on yield from other

276   factors, notably tree-crop interactions such as shade, is problematic.

277

278   4   Discussion

279   *4.1   Effects of temperate silvoarable systems on pest control and pollination*

280   *4.1.1   Invertebrate herbivores / pests*

281   Our analysis demonstrates a reduced arthropod herbivore abundance in silvoarable alleys

282   than in arable control conditions. This is consistent with the resource concentration hypothesis,

283   which predicts that specialist herbivores, i.e. those with a narrow host range, should be less

284   abundant in a more diverse system than a monoculture of just its host plant, due to the

285   masking of host chemical cues (Root, 1973). This hypothesis does not however extend to

286   generalist pests such as slugs, for which we find evidence of higher abundance in silvoarable

287   systems relative to arable controls, although these results were derived from only two sites.

288   Similar effects have been reported in and adjacent to flower-rich field margins (Eggenschwiler

289   et al., 2013; Frank, 1998), which suggests that areas which provide a refuge from tillage could

290   boost slug populations.

291   *4.1.2   Natural enemies*

292   The findings indicate the natural enemies of pests are more abundant in silvoarable alleys

293   compared with arable systems, although there are no clear differences in responses among

294   natural enemy taxa. The benefit to natural enemies could be explained by the resources

295   provided by silvoarable systems. For example, undisturbed tree rows could provide

296   overwintering refugia, which have been shown to be important for the maintenance of ground-

297   based natural enemy populations in other systems (Landis et al., 2000; Öberg et al., 2008;

298   Varchola and Dunn, 2001). Silvoarable systems could also enhance fine-scale complexity

299   which has been shown to benefit parasitoids (Chaplin-Kramer et al., 2011; Thies et al., 2005),

300   whilst tree rows could provide alternative food sources often required by this functional group

301   (Dyer and Landis, 1996; Murphy et al., 1998; Pfannenstiel et al., 2010).

4.1.3   Pollinators

303   Although study replication was low, the observed increase in pollinator abundance in

304   silvoarable systems compared with arable controls is consistent with the demonstrated

305   benefits of flowering strips and hedgerows (Garratt et al., 2017; Morandin and Kremen, 2013;

306   Nicholls and Altieri, 2013). This could be explained by the sheltered microclimate in silvoarable

307   systems, in addition to the potential for flowering resources in silvoarable tree rows, including

308   the understorey. The uncultivated tree rows could also provide nesting opportunities for

309   pollinators, as demonstrated by a previous modelling exercise which predicted that nesting

310   bee abundance would be increased by adopting silvoarable systems at a landscape scale

311   (Graham and Nassauer, 2017).

4.1.4   Magnitude of effects

313   Our reported mean effect sizes of 1.24 and 0.75 on natural enemy and arthropod

314   herbivore/pest abundances respectively are similar to those reported from meta-analyses of

315   other field scale enhancements such as polycultures, orchard vegetation management and

316   global (predominantly tropical) agroforestry, which range from 1.11 to 1.50 for natural

317   enemies, and 0.68 to 0.78 for pests (Iverson et al., 2014; Pumariño et al., 2015; Winter et al.,

318   2018). These effect sizes are, however, considerably smaller than those typically observed for

319   complex landscapes with a high proportion of non-crop habitats where, taking natural enemy

320   abundance as an example, the majority of studies report effect sizes of at least 2 compared

321   with simple large-scale landscapes (Bianchi et al., 2006).

322   *4.1.5   Effects on pest control and pollination services*

323   We find limited evidence of effects on pest control or pollination services, although there is

324   some evidence for higher ratios of airborne natural enemies to herbivores, pest mortality and

325   parasitism rates in silvoarable compared with arable systems. This limited evidence does

326   however support the expectations of Stamps and Linit (1997), who recognised the theoretical

327   potential for agroforestry systems to benefit pest control through plant diversification. Evidence

328   for corresponding effects on crop damage or yield is scarcer still, with contradictory evidence,

329   whilst evidence for pollination service is limited to a finding of higher California Poppy seedset

330   in silvoarable compared with arable systems across two sites (Varah, 2015). The economic

331   implications of pest control and pollination in silvoarable systems have yet to be assessed.

332

333   **4.2   A proposed framework for future research**

334   Agroforestry research in general is constrained by the suitability of appropriately scaled field

335   sites designed for experimental vigour with proper controls (Stamps and Linit, 1999), which

336   poses unique challenges to evaluating the factors which influence variation in effects. We

337   therefore propose a framework to predict how these factors influence the observed

338   abundances of natural enemies, pests and pollinators in temperate silvoarable systems (Fig.

339   4). For each identified factor which could influence variation, we refer to evidence from the

340   studies included in our analysis and, as these are limited, ecological theory and evidence from

341   analogous systems, where available, to form a series of hypotheses which can be tested by

342   future research.

343
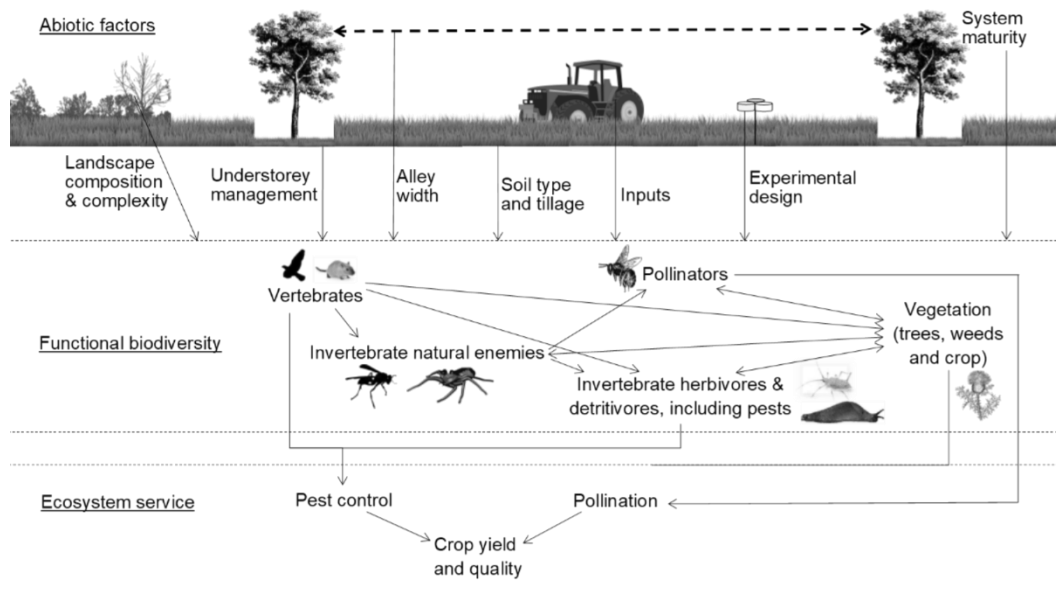
Fig. 4. Illustrative summary of the key factors predicted to influence functional biodiversity in temperate silvoarable systems, the major interactions between functional groups and their contribution to pest control and pollination.

4.2.1 Soil type and tillage

Although direct evidence is lacking, soil type could be critical in the outcome of pest control based on the evidence for slug problems in silvoarable systems. For example, a major slug pest, *Deroceras reticulatum*, favours fine-textured soils with high moisture content (Ondina et al., 2004), suggesting that silvoarable systems on such soil types could be prone to higher pest damage. Further research could investigate whether adapting soil cultivation in silvoarable systems could help mitigate this damage, for example, by modifying tillage depth, timing and/or frequency (Roger-Estrade et al., 2010).

4.2.2 Inputs

Our findings of enhanced natural enemy activity and reduced pest pressure in silvoarable alleys compared with arable controls suggest that pesticide inputs in non-organic systems could potentially be reduced without compromising productivity, as demonstrated for hedgerow restoration (Morandin et al., 2016). Furthermore, an enhanced level of pest control

362   in organic silvoarable systems compared with arable controls could reduce crop loss to pests.

363   These hypotheses warrant further investigation.

364   *4.2.3   Alley width*

365   Alley width is typically constrained by the size of machinery in temperate regions. Although

366   there is a strong bias in the literature towards systems with alley widths of around 12 m (Fig.

367   2b), three studies included in our analysis found that tree rows or the edges of crop alleys

368   support greater abundances of natural enemies and lower pest abundances than the centre

369   of crop alleys (Peng et al., 1993; Phillips et al., 1994; Rekany, 2015). Furthermore, stronger

370   distribution patterns of predators have been observed in 50 m crop alleys compared with 24 m

371   alleys (Rekany, 2015). This broadly corresponds to studies of woody field boundaries, which

372   find highest abundances of natural enemies and pollinators at around 2 to 10 m from the

373   boundary, before rapidly declining (Lewis, 1969; Morandin et al., 2014). Future research could

374   therefore test whether narrow alley widths have the greatest benefit on pollination and natural

375   enemy activity.

376   *4.2.4   Understorey management*

377   Two of the studies included in our analysis compared vegetated understoreys with chemically

378   weeded understoreys. A study of aphid natural enemies found no effect between treatments,

379   possibly because the vegetated treatment did not properly establish (Smits et al., 2012).

380   However, Burgess et al. (2003) found fewer slugs and more spiders in alleys adjacent to

381   vegetated versus bare understoreys, suggesting that understorey vegetation promotes pest

382   control, although there was little difference in carabid beetle abundance between treatments.

383   Nevertheless, management of silvoarable tree rows to promote tussock-forming grasses could

384   replicate the benefits of beetle banks (Collins et al., 2003), which is worthy of further

385   investigation.

386   In addition, evidence from flower strips shows that mixes rich in pollen and nectar are most

387   beneficial to pollinators, whilst natural enemies appear to be less strongly associated with

388   vegetation type (reviewed in Haaland et al. (2011)). Nevertheless, flower strips designed to

389   benefit natural enemies of wheat pests have been successful in reducing pest pressure

390   (Tschumi et al., 2015). A similar tailored approach could be investigated in silvoarable

391   systems.

4.2.5   Maturity

393   The longest-running study in our analysis found that the slug population increased over the

394   course of four years in a young silvoarable system compared with a control plot (Griffiths et

395   al., 1998), whilst the abundance and/or diversity of birds and small mammals has also been

396   shown to increase with system maturity (Gibbs et al., 2016; Klaa et al., 2005). Conversely, the

397   abundance and diversity of epigeal invertebrate predators showed no significant response to

398   field margin and hedgerow age in the UK, suggesting rapid colonisation, although some

399   species were more closely associated with mature habitat (Pywell et al., 2005). We

400   recommend that this could be investigated through long-term studies of invertebrate

401   communities in silvoarable systems.

4.2.6   Vegetation

403   Two of the studies included in our analysis considered diversity and abundance of vascular

404   plants in silvoarable versus arable systems, finding higher plant species richness in silvoarable

405   alleys (Varah, 2015) and greater cover of non-crop plants, especially adjacent to vegetated

406   understoreys, possibly due to seed-spread during cutting (Burgess et al., 2003). In contrast,

407   lower numbers of weeds were found in a silvoarable system in France relative to an arable

408   control early in the season, despite a higher species richness in the silvoarable system

409   (Meziere et al., 2016). This contrast among studies could be explained by the differing abilities

410   of weed species to ingress from perennial habitats (Marshall, 2004). Therefore, we would

411   predict that weed problems in silvoarable systems will be highly context-dependent. Weed

412   cover could also provide a mechanism for the observed benefits on natural enemies and

413   pollinators in silvoarable systems, as demonstrated by a positive association of carabid beetle

414   activity with weed cover in one of the studies in our analysis (Sharman, 2015).

19

415   The choice of tree species could influence micro-climatic conditions and provide resources

416   such as nectar for functional groups. Studies of hedgerows and agroecosystems generally

417   show that plant diversity enhances natural pest control and pollination services (Garratt et al.,

418   2017; Isbell et al., 2017; Letourneau et al., 2011), and we would predict this to apply to

419   silvoarable systems. On the contrary however, interplanting shrubs within apple tree rows did

420   not influence pest or natural enemy communities in one silvoarable system (Kranz et al.,

421   2018), although confirmatory evidence is needed from other systems to improve our

422   understanding of the influence of tree species and diversity on pest control and pollination.

423   The choice of arable crop may also influence results, for example, the study with the weakest

424   effect size for pollinators was of a pea crop, possibly because of the attractant effect of the

425   mass-flowering resource in the control plot compared with studies based on cereal crops.

426   Long-term and/or multiple-site studies would further test this hypothesis.

427   *4.2.7 Trophic interactions among fauna*

428   In general, the efficacy of conservation biological control is dependent on synergistic or

429   antagonistic interactions between natural enemies (Straub et al., 2008; Thies et al., 2011),

430   whilst predation of pollinators could reduce fruit set (Dukas, 2005). Few studies in our analysis

431   considered these interactions, although positive correlations have been demonstrated

432   between spiders and carabid beetles in a North American silvoarable system, suggesting

433   limited interference (Stamps et al., 2009b).

434   Interactions between vertebrates and invertebrates could also play a role in pest control and

435   pollination, particularly given the potential benefits of silvoarable systems on vertebrate

436   populations. A literature search on vertebrates in temperate silvoarable systems yielded four

437   additional studies (Supplementary Material 2), which reported increased abundance and/or

438   species richness of small mammals (Klaa et al., 2005; Wright, 1994), bats (Disca, 2003) and

439   birds (Gibbs et al., 2016; Williams et al., 1995). Vertebrates could benefit pest control through

440   direct predation of pests (e.g. Kunz et al. (2011); Whelan et al. (2008)). On the other hand,

441   vertebrates could directly cause pest problems, for example crop damage arising from roe

442   deer, rabbits, wild boar and pigeons have been anecdotally reported in silvoarable systems

443   (Gosme, 2014; Newman et al., 2018; Smith et al., 2016). Vertebrates could also disrupt natural

444   enemy functionality (Martin et al., 2013), for example, an apparent increase in rats correlated

445   with a substantial decrease in carabid beetle abundance in a silvoarable system (Stamps et

446   al., 2009b). Interactions are therefore an important avenue for further research given their

447   implications for pest control and potentially pollination.

448   *4.2.8   Landscape composition and complexity*

449   Two of the studies included in our analysis identified that proximity to treed landscape features

450   (forestry plots or boundary hedgerows) outside of the silvoarable system influenced their

451   results, benefitting pest parasitism and pollinator abundance respectively (Muhammad et al.,

452   2005; Varah, 2015). The study with the second-lowest calculated effect size of natural enemy

453   abundance noted that the diversity of the surrounding landscape may have masked any

454   benefit of the silvoarable system (Smits et al., 2012), whilst a well-studied system in an

455   intensive agricultural landscape had relatively strong effect sizes for natural enemies and

456   pollinators (Rekany, 2015; Sharman, 2015; Varah, 2015). This is supported by landscape-

457   scale studies of pest control and pollination, which suggest that functionality is high in diverse

458   landscapes (Holzschuh et al., 2007), such that field-scale enhancements are more likely to be

459   effective in simple landscapes, defined as 1-20% of non-crop habitat (Tscharntke et al., 2005).

460   Although this hypothesis would be difficult to vigorously test in silvoarable systems, a

461   standardised experimental design across a network of sites with similar characteristics but

462   differing landscape context would help to predict those landscapes in which silvoarable

463   systems would be most effective in terms of natural pest control and pollination.

464   *4.2.9   Experimental design*

465   Our results show that effect sizes in silvoarable systems tend to be relatively small compared

466   with landscape-scale studies, and so experiments should be designed to have sufficient power

467   to detect effect sizes of 10 to 30 % (Fig. 3). Experimental design and analysis should take

468   limitations of survey techniques into account, for example, the inclusion of pitfall trap data

469   collected from tree rows with complex understoreys in comparisons between silvoarable and

470   arable systems could bias results against silvoarable systems (Thomas et al., 2006), as

471   indicated by our analysis (Supplementary Material 3). Differences between the silvoarable and

472   arable control plots could also influence results, particularly differences in historical land use,

473   environmental conditions (including soil type), crop selection, management, proximity to

474   landscape features and proximity between treatment and control plots.

475

4.3   Study limitations

477   Our analysis of pests, natural enemies and pollinators focusses on invertebrates, as other

478   taxa have been scarcely studied in temperate silvoarable systems and predicting their net

479   effect on pest control and pollination is often more complex than for most invertebrates.

480   Nevertheless, we consider plants and vertebrates and their potential implications for pest

481   control and pollination in our predictive framework above.

482   Pests of the arable crop component of silvoarable systems are the focus of the study, rather

483   than pests of the tree component which have been scarcely studied. Nevertheless, there is

484   some evidence that aphid densities are lower in silvoarable tree rows than in forestry controls

485   (Naeem and Compton, 2000; Naeem et al., 1997). Two studies have referred to pest damage

486   in silvoarable apple trees compared with orchards, although results are inconclusive and

487   appear to vary according to pest taxa and fruit stage (Kranz et al., 2018; Smith et al., 2014).

488   Our analysis pools together numbers of captures/observations for different taxa recorded in

489   each study, therefore, numerically abundant species are well represented in effect sizes

490   compared with less abundant species, regardless of their body size or effect on pest control

491   or pollination. Given that small sized carabid beetles were trapped at higher abundance in

492   silvoarable compared with arable systems, in contrast to large generalist species (Rekany,

493   2015), accounting for body size could reduce effect sizes, although the situation is complex

494   as larger carabid species could also predate smaller carabids (e.g. Prasad and Snyder
495   (2006)), thereby antagonising pest control.

496   The analysis of pooled numbers of captures/observations does not take diversity into account,
497   as only two of the studies report on diversity of functional groups, finding significantly higher
498   diversities of invertebrate predators, herbivores and parasitic Hymenoptera in silvoarable
499   relative to arable systems (Howell, 2001; Stamps et al., 2002).

500   Whilst our analysis goes some way to comparing pests, natural enemies and pollinators in
501   silvoarable systems compared with arable, more research is needed to quantify subsequent
502   effects on pest control and pollination service outcome.

503 **5   Conclusion**

504   We find evidence for significantly enhanced natural enemy populations and significantly
505   supressed arthropod herbivore populations in silvoarable systems, but molluscan pests were
506   more numerous in the two available studies, compared with arable. Pollinators were also more
507   abundant in silvoarable than arable systems, but study replication was low. This suggests a
508   higher efficacy of pollination and natural pest control in silvoarable crop alleys compared with
509   arable systems, although crop damage from slugs could cause problems on some farms. Our
510   findings therefore provide further support for the role of silvoarable systems in sustainable
511   intensification, in conjunction with the demonstrated benefits to other ecosystem services (e.g.
512   Smith et al. (2013); Torralba et al. (2016); Tsonkova et al. (2012)). Nevertheless, further well-
513   replicated empirical research or modelling studies are required to test our predictive framework
514   of the factors which influence pests, natural enemies and pollinators in silvoarable systems,
515   in addition to measures of pest control and pollination, and their implications for productivity,
516   economic output and resilience.

Acknowledgements

Supplementary Material

Supplementary Material 1. Flow diagram for literature selection based on PRISMA.

Supplementary Material 2. Attributes of reviewed literature.

Supplementary Material 3. Effect sizes of natural enemy and pest/herbivore abundances or activity densities (used to inform Fig. 3).

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