

# *Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination*

Article

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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

5

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19

## 20 **Abstract**

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

42

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

## 45 **1 Introduction**

46 Global crop demand is rising rapidly, and is forecasted to increase by 100-110% from 2005 to  
47 2050 (Tilman et al., 2011). The intensification of arable production in temperate regions has  
48 driven declines in biodiversity and associated ecosystem services, such as pest control and  
49 pollination (Bartomeus et al., 2014; Bianchi et al., 2006). This has in many cases led to a  
50 reliance on management techniques such as pesticide application, genetically modified crops  
51 and maintenance of managed honey bee colonies. The sustainability of such management  
52 practices is threatened by processes such as pesticide resistance (Sparks and Nauen, 2015),  
53 secondary pest outbreaks (Dutcher, 2007; Hill et al., 2017), depletion of non-renewable  
54 sources, environmental and human health risks associated with pesticides (Bernardes et al.,  
55 2015; Kim et al., 2017), and honey bee colony collapse or growth deficits (Aizen and Harder,  
56 2009; Neumann and Carreck, 2010).

57 There is a strong and growing pressure to move towards more sustainable intensification of  
58 production, through harnessing natural processes to sustain productivity rather than relying  
59 on pesticides and managed pollinators (FAO, 2013; Power, 2010). One alternative tactic for  
60 reducing crop damage by pests is to enhance the effectiveness of their natural enemies, such  
61 as predators and parasitoids, by enhancing plant diversity and habitat complexity (Begg et al.,  
62 2017). This is the principle of conservation biological control (Barbosa, 1998). Similar  
63 arguments have been proposed to encourage wild pollinators (Kovács-Hostyánszki et al.,  
64 2017; Woodcock et al., 2016), which have the potential to increase the effectiveness of  
65 pollination in flowering crops and mitigate against potential honey bee losses (Garibaldi et al.,  
66 2013; Hoehn et al., 2008).

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

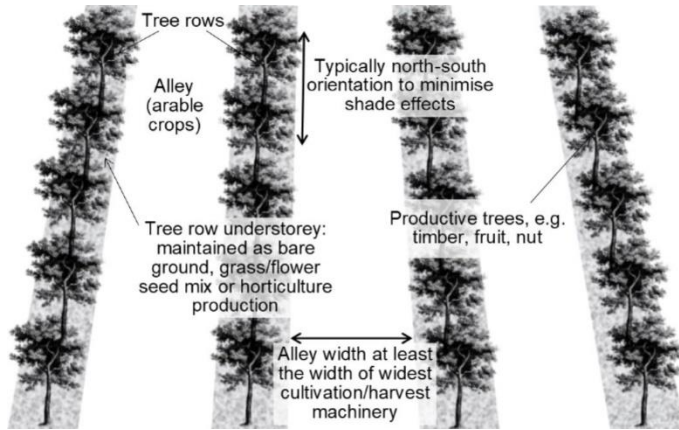
71 by mechanisation and climatic factors such as light availability, there is growing interest in this  
72 land use system in temperate regions because of its potential contribution towards sustainable  
73 intensification (Newman and Gordon, 2018; Smith et al., 2012). For example, the  
74 'establishment, 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,

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



101

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

## 109 **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 40°

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

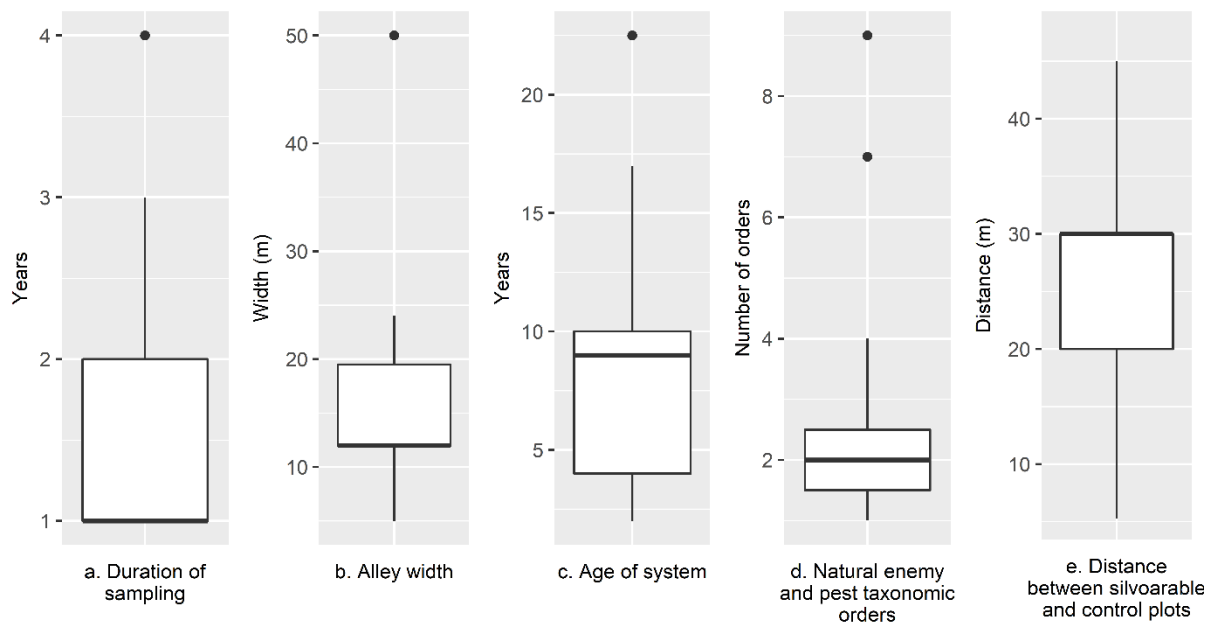
### 186 **3 Results**

#### 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



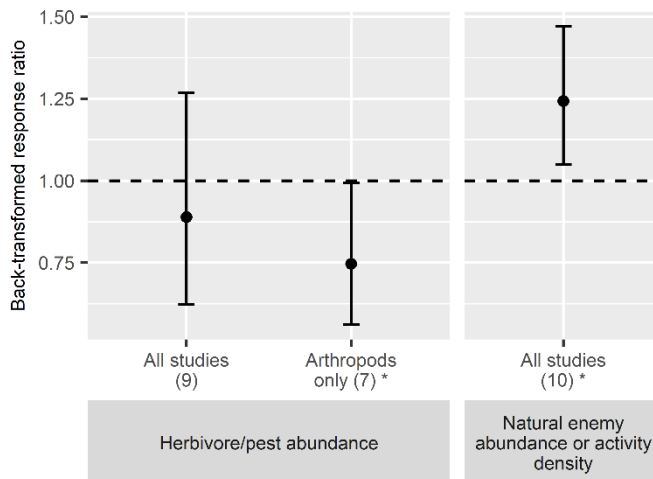
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199 **Fig. 2.** Characteristics of studies of invertebrate pest control and pollination in temperate silvoarable  
 200 systems, where the relevant information is specified (Supplementary Material 2). For studies of multiple  
 201 sites, each site 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.

### 205 **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 ( $z=-0.650$ ,  $p\text{-value}=0.516$ ). However, the abundance of arthropod herbivores/pests was  
 209 significantly lower in the silvoarable than arable systems ( $z=-2.005$ ,  $p\text{-value}=0.045$ ), 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.

212 Natural enemy abundance was significantly higher in silvoarable compared with arable  
 213 systems ( $z=2.528$ ,  $p\text{-value}=0.011$ ), with a mean effect size of 1.24 (Fig. 3). Only one of the  
 214 nine natural enemy effect sizes were less than one (Supplementary Material 3).



215

216 **Fig. 3.** Means and confidence intervals of the back-transformed response ratios of invertebrate  
 217 herbivore/pest and natural enemy abundance in silvoarable alleys (treatment) versus arable fields  
 218 (control). A response ratio of greater than 1 indicates a higher abundance in the silvoarable than the  
 219 arable system. Numbers in parentheses represent the number of studies and “\*” denotes significance  
 220 ( $p\text{-value} < 0.05$ ). Data is provided in Supplementary Material 3.

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

### 227 **3.3 Proxies for pest control**

228 One measure of pest control is the ratio of the number of natural enemies to herbivores/pests.  
 229 Two studies found a higher ratio in silvoarable versus arable systems (Table 1), which could  
 230 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, <i>Bombus</i>	1.17	Yes
Howell (2001)	Andrenidae, Apidae, Colletidae, Halictidae, Megachilidae,	1.72	No
Varah (2015): 2 sites	Syrphidae, <i>Bombus</i> (solitary bees excluded as silvoarable data not separable from silvopasture data)	2.55	No
	Seedset in <i>Eschscholtzia californica</i> 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).

#### 302 *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).

#### 312 *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*

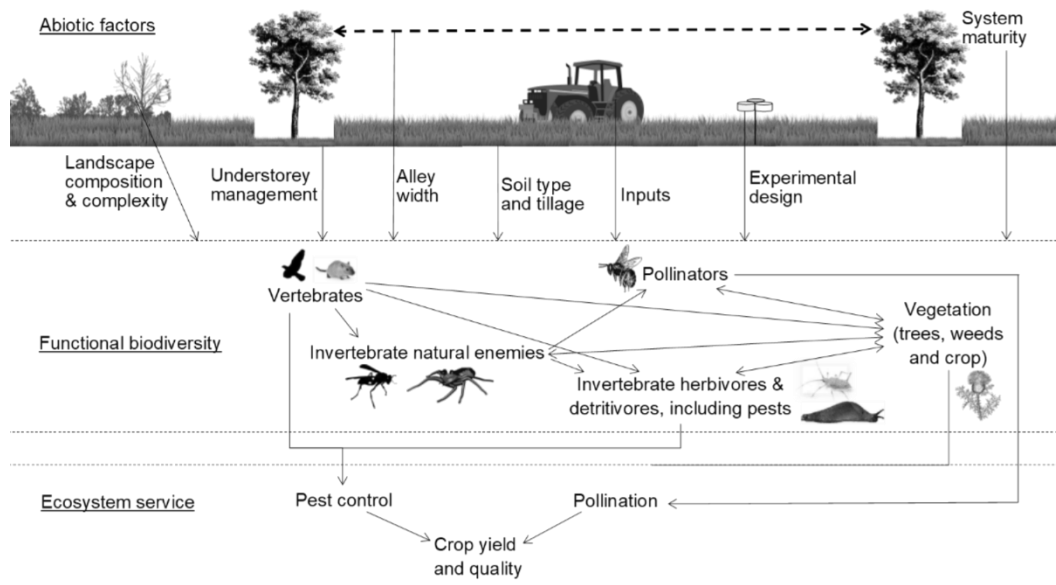
323 We find limited evidence of effects on pest control or pollination services, although there is  
324 some evidence for higher ratios of airborne natural enemies to herbivores, pest mortality and  
325 parasitism rates in silvoarable compared with arable systems. This limited evidence does  
326 however 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



344

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

348

349 *4.2.1 Soil type and tillage*

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

357 *4.2.2 Inputs*

358 Our findings of enhanced natural enemy activity and reduced pest pressure in silvoarable  
 359 alleys compared with arable controls suggest that pesticide inputs in non-organic systems  
 360 could potentially be reduced without compromising productivity, as demonstrated for  
 361 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.

#### 392 *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.

#### 402 *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).

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

### 476 **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 suppressed 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.

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## 523 **Supplementary Material**

524 Supplementary Material 1. Flow diagram for literature selection based on PRISMA.  
525 Supplementary Material 2. Attributes of reviewed literature.  
526 Supplementary Material 3. Effect sizes of natural enemy and pest/herbivore abundances or  
527 activity densities (used to inform Fig. 3).

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