



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

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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

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6 Authors: Tom Staton^{a,*}, Richard J Walters^b, Jo Smith^c, Robbie D Girling^a

7 ^a School of Agriculture, Policy and Development, University of Reading, Reading, UK

8 ^b Department of Biology, Lund University, Lund, Sweden

9 ^c Organic Research Centre, Elm Farm, Newbury, UK

10 * Corresponding author. E-mail address: t.staton@pgr.reading.ac.uk

11

12 Other author email addresses:

13 richard.walters@biol.lu.se

14 jo.s@organicresearchcentre.com

15 r.girling@reading.ac.uk

16

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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

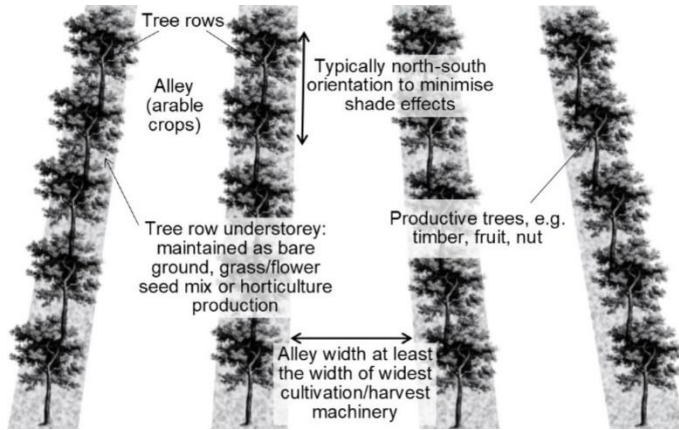
71 by mechanisation and climatic factors such as light availability, there is growing interest in this
72 land use system in temperate regions because of its potential contribution towards sustainable
73 intensification (Newman and Gordon, 2018; Smith et al., 2012). For example, the
74 'establishment,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

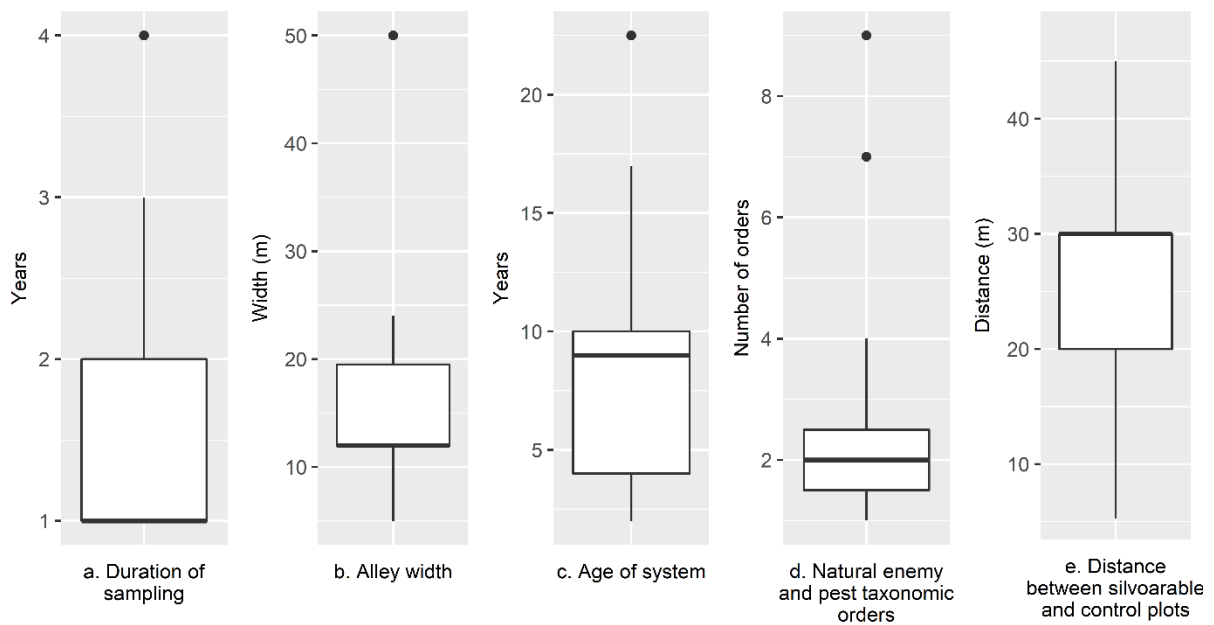
186 **3 Results**

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



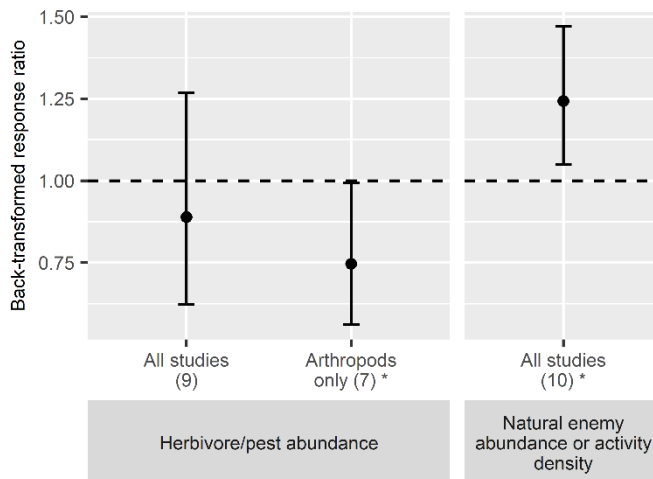
198

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.

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*

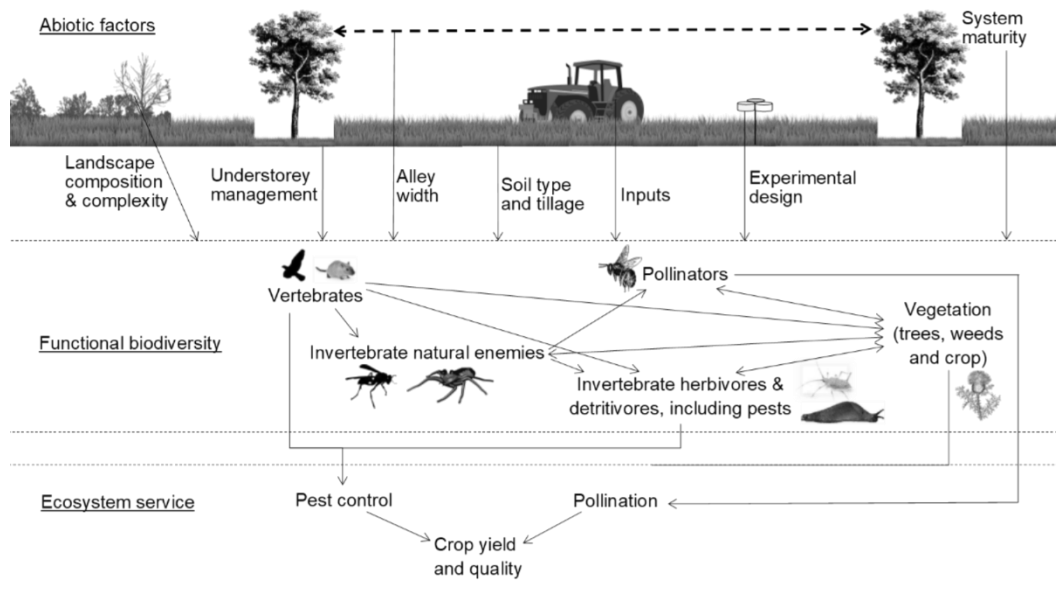
323 We find limited evidence of effects on pest control or pollination services, although there is
324 some evidence for higher ratios of airborne natural enemies to herbivores, pest mortality and
325 parasitism rates in silvoarable compared with arable systems. This limited evidence does
326 however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