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

Article

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Title page

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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 by mechanisation and climatic factors such as light availability, there is growing interest in this land use system in temperate regions because of its potential contribution towards sustainable intensification (Newman and Gordon, 2018; Smith et al., 2012). For example, the ‘establishment, regeneration or renovation of agroforestry systems’ is promoted through the European Union’s Common Agricultural Policy. Agroforestry is perceived as being beneficial for the environment and land stewardship, which are typically the main drivers for adoption (García de Jalón et al., 2018; Matthews et al., 1993).

Of particular interest in terms of the potential benefit from natural pest control and pollination is silvoarable agroforestry, which is the intercropping of trees or shrubs with arable crops (Fig. 1). Different methods of silvoarable production are practiced throughout northern temperate regions, sometimes being referred to by regional terminologies. These include tree-based intercropping and alley cropping systems in North America which typically use hardwoods for nut and timber production, and various agri-silviculture systems in the Himalayas (Newman and Gordon, 2018). Timber is typically the main tree product produced in silvoarable systems, although intercropping with fruit trees is widely practised in China (Chang et al., 2018) and its potential for a quick return on investment is encouraging uptake in the UK (Newman et al., 2018). Silvoarable systems are far scarcer in southern temperate regions, although research platforms have been established (Newman and Gordon, 2018). Temperate silvoarable systems have the potential to increase productivity compared with equivalent monocropped land, for example Land Equivalent Ratios of between 0.98 and 1.37 have been estimated over the full tree rotation (Graves et al., 2010; Gruenewald et al., 2007).

Several reviews and meta-analyses have demonstrated that temperate agroforestry systems generally enhance biodiversity and some ecosystem services compared with arable cropping (Smith et al., 2013; Stamps and Linit, 1997; Torralba et al., 2016; Tsonkova et al., 2012). However, the effects of silvoarable systems on pest control and pollination services remain poorly understood in temperate regions; all but two of 42 studies included in a recent meta-analysis of pest, disease and weed control were conducted in the tropics and sub-tropics, which typically have different mechanisation requirements and utilise different tree/crop combinations to those used in temperate regions (Pumariño et al., 2015).

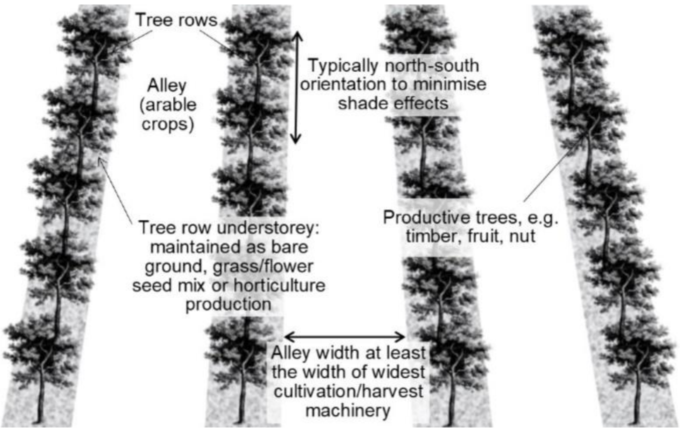

Fig. 1. Illustration of a typical silvoarable alley-cropping system.

The aims of this review are: 1) to collate and analyse studies of pollinators, pests and their natural enemies in temperate silvoarable systems, specifically in terms of their potential contribution to pest control and pollination ecosystem services; and 2) to develop a framework for future research to predict the factors which influence variation in results, with the aspiration of driving forward a unified research agenda.

2 Methods

Literature was sourced based on the following criteria (the selection process is summarised at Supplementary Material 1):

1. A measure of abundance or activity density of invertebrate herbivores/pests, natural enemies or pollinators, and/or a measure of conservation biological control of animal pests and/or pollination were recorded;
2. Studies were undertaken in a temperate region, defined as latitude greater than 40º

north or south;

3. A silvoarable system, for this purpose defined as trees or shrubs incorporated into an arable field, was compared with an arable control, with the respective arable components comprising annual crops.

To minimise the risk of publication bias, we sourced both peer-reviewed and non-peer-reviewed literature, including theses and reports.

2.1 Data extraction

A total of 19 datasets were identified (Supplementary Materials 2 and 3). We reviewed the characteristics of each study and the studied system(s), including sampling duration, alley width, system age, number of taxonomic orders studied and minimum distance between silvoarable and arable control plots. Capture or abundance data for natural enemies, pests (or herbivores where pest species were not specified), pollinators, and pest control proxies was sourced from each dataset to analyse effect sizes. Where necessary, data was extracted from figures using GetData Graph Digitizer (version 2.26, http://getdata-graph-digitizer.com). Any data collected from tree rows was excluded where possible to provide a comparison of silvoarable alleys versus arable. Where pitfall trap data from tree rows could not be excluded, the study/site was omitted entirely from the analysis of effect sizes, because the structural complexity of vegetation in tree rows could reduce capture rates (Melbourne, 1999; Thomas et al., 2006). One study was completely excluded and one study partially excluded (two of the three sites) on this basis (Supplementary Material 3).

2.2 Meta-analysis for herbivores/pests and natural enemies

To quantify the magnitude of effects for herbivores/pests and natural enemies, we calculated effect size as the log response ratio (Hedges et al., 1999) of mean functional group abundance in the silvoarable system versus the arable control. Hence, the response variables were herbivore/pest abundance and natural enemy abundance. The single explanatory variable was presence or absence of a silvoarable system.

Standard deviations could not be extracted for four of the 12 identified studies (Supplementary Material 3), so were imputed based on their mean values (Lajeunesse, 2013). Three of the four studies with missing standard deviations used pitfall trapping, therefore imputed standard deviations were calculated based on the significant linear relationship between mean and standard deviation for the two available pitfall trap studies with standard deviation data (Griffiths et al., 1998; Phillips et al., 1994). The significance of effects for herbivore/pest and natural enemy abundances were analysed in a mixed-effects meta-analysis model, using the rma.mv function of the metaphor package version 2.1-0 (Viechtbauer, 2010) within R version 3.5.2 (R Core Team, 2018). As multiple data points were extracted from some individual studies, study ID was included as a random effect. The results are reported as back-transformed values.

The imputation of standard deviations did not increase the risk of Type 1 errors, as effect sizes were reduced and p-values increased, compared with models which omitted studies with missing standard deviations. Outliers and influential observations were quantified using Cook's distance. For the pest/herbivores model, Cook's distance for a slug abundance data point was 0.30, compared with less than 0.05 for all other data points. Therefore, the results of a model excluding slug data (i.e. arthropods only) are also presented. For the natural enemies model, the data-point with the highest Cook's distance (0.13) was a negative effect size (i.e. lower abundance in the silvoarable plot than arable control) and was therefore retained to reduce the likelihood of a Type 1 error. Cook's distance was below 0.10 for all other data points. Publication bias was considered unlikely due to the inclusion of unpublished studies, but funnel plots were visually checked for symmetry. Heterogeneity, in the form of I^2 calculated from the models without random effects, ranged from 56% to 75%, lower than the median of 85% reported for ecological meta-analyses (Senior et al., 2016).

2.3 Review of other effect sizes

Effect sizes were calculated from five studies which reported a proxy for pest control, such as ratios of natural enemies to herbivores, pest mortality rates or pest parasitism rates, in a silvoarable system versus an arable control. Pollinator effect sizes were derived from three studies which reported abundances in silvoarable systems and arable controls. To investigate whether the functional group responses are highly influenced by any specific taxa, effect sizes were also calculated for taxa which were included in three or more studies (Araneae, Carabidae, Coccinellidae, Syrphidae and Aphididae). We calculated effect size as the mean abundance (or for pest control proxies, the mortality/parasitism rate or ratio of natural enemies to pests) in the silvoarable system, divided by the respective value for the arable control. Due to the low number of available studies for these measures, pooled effect sizes were not analysed. Finally, four studies reported some measure of crop damage or yield, which we describe in the Results.

2.4 Predictive framework

Our findings were used to inform and construct a predictive framework for future research, which identifies a series of hypotheses to predict the factors which influence variation in the results. The components of the framework were selected based on a wider review of ecological theory and analogous systems, such as hedgerows, field margins, flower strips and beetle banks.

3 Results

3.1 Characteristics of studies

A total of 19 datasets were extracted from 17 studies undertaken in five countries, comprising Canada, France, Turkey, UK and USA, with publication dates ranging from 1993 to 2015 (Supplementary Material 2). Data from the majority of the studies included in our analysis were taken from single sites over less than two years (Fig. 2a). There was a strong bias towards systems with alley widths of around 12 m (Fig. 2b). Most of the studied systems were relatively young in age, i.e. less than ten years since planting (Fig 2c). The majority of studies report on the abundances of three or fewer taxonomic orders, with only two studies reporting on seven or more orders (Fig. 2d). Where the minimum distance between the silvoarable and arable plots is specified, this is typically less than 50 m (Fig 2e, three outliers are not shown).

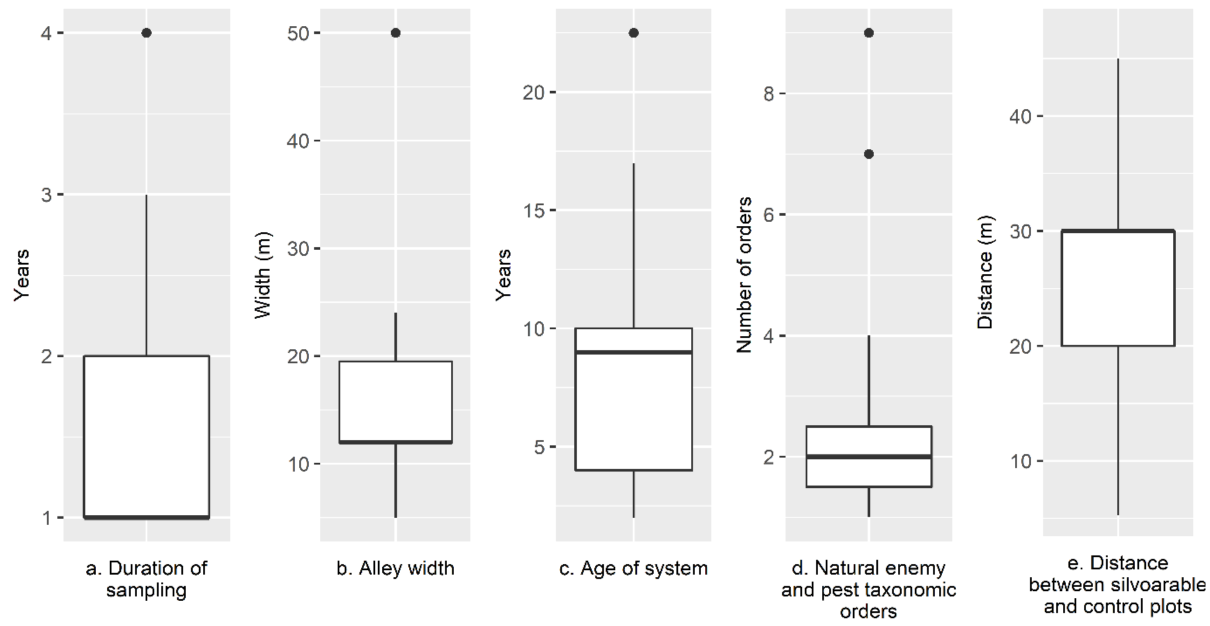

Fig. 2. Characteristics of studies of invertebrate pest control and pollination in temperate silvoarable systems, where the relevant information is specified (Supplementary Material 2). For studies of multiple sites, each site is represented individually. Multiple studies reporting on the same data are represented once collectively. Each ‘box’ represents the first and third quartiles, whilst the ‘whiskers’ extend to the largest/smallest value no further than 1.5 * inter-quartile range from the box. Three outliers are not 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

Invertebrate herbivore/pest abundances were lower in the silvoarable compared with arable systems, with a back-transformed mean effect size of 0.89 (Fig. 3), but this was not significant (z=-0.650, p-value=0.516). However, the abundance of arthropod herbivores/pests was significantly lower in the silvoarable than arable systems (z=-2.005, p-value=0.045), with a mean effect size of 0.75 (Fig. 3). This contrasts to slug abundance, which was higher in the 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).

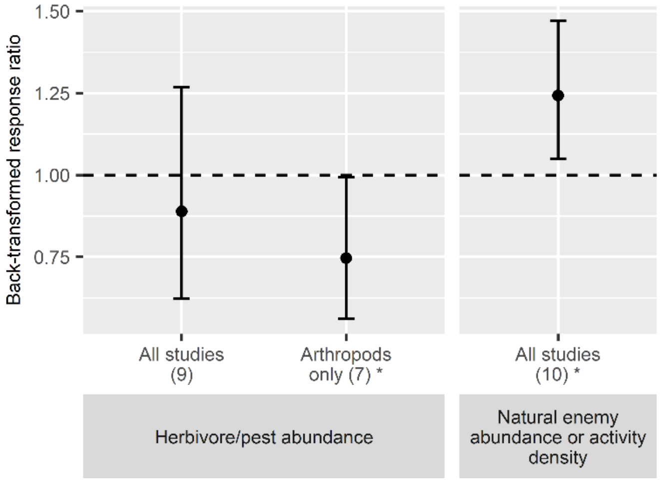

Fig. 3. Means and confidence intervals of the back-transformed response ratios of invertebrate herbivore/pest and natural enemy abundance in silvoarable alleys (treatment) versus arable fields (control). A response ratio of greater than 1 indicates a higher abundance in the silvoarable than the arable 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 rates of pests, and all found consistently higher rates in silvoarable systems compared with arable systems (Table 1), again suggesting a higher level of pest control.

Table 1

Summary of studies which reported proxies for pest control, i.e. ratios of airborne natural enemies to herbivores or mortality/parasitism rates. Effect sizes are calculated as the 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)

3.4 Pollinator abundance

Only three studies, in the UK and Canada, reported abundances of pollinating insects in silvoarable systems and arable controls. Effect sizes ranged from 1.17 to 2.55, indicating beneficial effects on pollinator populations in silvoarable systems compared with arable controls (Table 2), but study replication was low. One study also reported higher California Poppy phytometer seedset by a factor of 4.5 in agroforestry compared with arable systems (Table 2).

Table 2

Effect sizes for studies which reported pollinator abundances or pollination service, calculated as pollinator abundance or seedset in the silvoarable system divided by the respective value 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

3.5 Taxon-specific effects

The results were also analysed for aphids and four taxa of predators comprising Araneae, Carabidae, Coccinellidae and Syrphidae. The effect sizes were highly variable, ranging below and above 1 in four of the five taxa analysed (Table 3). The only taxon represented by at least three studies which had consistently higher numbers in silvoarable systems compared with arable controls was hoverflies (Syrphidae).

Table 3

Effect sizes for five of the most commonly studied taxa in temperate silvoarable systems, calculated as total or mean abundance in the silvoarable system divided by the respective 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	-	-	-

3.6 Implications for crop damage and yield

Evidence of crop damage by invertebrate pests is very limited, and only two studies have attempted to establish a link between pest control and yield of the arable component. Griffiths et al. (1998) recorded higher slug damage to a pea crop in a UK silvoarable system compared with an arable control, with damage level positively correlated to slug captures. However, yield was not measured. In Turkey, Akbulut et al. (2003) observed a lower level of crop damage from invertebrates in silvoarable plots, accompanied by higher yield of beans but lower yield of maize, relative to arable. Other studies have simultaneously sampled cereal yields and invertebrates in silvoarable systems, finding lower silvoarable yields compared with arable in conventional systems (Burgess et al., 2003), and the opposite result in organic systems (Varah, 2015), but disentangling the effect of pest control or pollination on yield from other factors, notably tree-crop interactions such as shade, is problematic.

4 Discussion

4.1 Effects of temperate silvoarable systems on pest control and pollination

4.1.1 Invertebrate herbivores / pests

Our analysis demonstrates a reduced arthropod herbivore abundance in silvoarable alleys than in arable control conditions. This is consistent with the resource concentration hypothesis, which predicts that specialist herbivores, i.e. those with a narrow host range, should be less abundant in a more diverse system than a monoculture of just its host plant, due to the masking of host chemical cues (Root, 1973). This hypothesis does not however extend to generalist pests such as slugs, for which we find evidence of higher abundance in silvoarable systems relative to arable controls, although these results were derived from only two sites. Similar effects have been reported in and adjacent to flower-rich field margins (Eggenschwiler et al., 2013; Frank, 1998), which suggests that areas which provide a refuge from tillage could boost slug populations.

4.1.2 Natural enemies

The findings indicate the natural enemies of pests are more abundant in silvoarable alleys compared with arable systems, although there are no clear differences in responses among natural enemy taxa. The benefit to natural enemies could be explained by the resources provided by silvoarable systems. For example, undisturbed tree rows could provide overwintering refugia, which have been shown to be important for the maintenance of ground-based natural enemy populations in other systems (Landis et al., 2000; Öberg et al., 2008; Varchola and Dunn, 2001). Silvoarable systems could also enhance fine-scale complexity which has been shown to benefit parasitoids (Chaplin-Kramer et al., 2011; Thies et al., 2005), whilst tree rows could provide alternative food sources often required by this functional group (Dyer and Landis, 1996; Murphy et al., 1998; Pfannenstiel et al., 2010).

4.1.3 Pollinators

Although study replication was low, the observed increase in pollinator abundance in silvoarable systems compared with arable controls is consistent with the demonstrated benefits of flowering strips and hedgerows (Garratt et al., 2017; Morandin and Kremen, 2013; Nicholls and Altieri, 2013). This could be explained by the sheltered microclimate in silvoarable systems, in addition to the potential for flowering resources in silvoarable tree rows, including the understorey. The uncultivated tree rows could also provide nesting opportunities for pollinators, as demonstrated by a previous modelling exercise which predicted that nesting bee abundance would be increased by adopting silvoarable systems at a landscape scale (Graham and Nassauer, 2017).

4.1.4 Magnitude of effects

Our reported mean effect sizes of 1.24 and 0.75 on natural enemy and arthropod herbivore/pest abundances respectively are similar to those reported from meta-analyses of other field scale enhancements such as polycultures, orchard vegetation management and global (predominantly tropical) agroforestry, which range from 1.11 to 1.50 for natural enemies, and 0.68 to 0.78 for pests (Iverson et al., 2014; Pumariño et al., 2015; Winter et al., 2018). These effect sizes are, however, considerably smaller than those typically observed for complex landscapes with a high proportion of non-crop habitats where, taking natural enemy abundance as an example, the majority of studies report effect sizes of at least 2 compared with simple large-scale landscapes (Bianchi et al., 2006).

4.1.5 Effects on pest control and pollination services

We find limited evidence of effects on pest control or pollination services, although there is some evidence for higher ratios of airborne natural enemies to herbivores, pest mortality and parasitism rates in silvoarable compared with arable systems. This limited evidence does however support the expectations of Stamps and Linit (1997), who recognised the theoretical potential for agroforestry systems to benefit pest control through plant diversification. Evidence for corresponding effects on crop damage or yield is scarcer still, with contradictory evidence, whilst evidence for pollination service is limited to a finding of higher California Poppy seedset in silvoarable compared with arable systems across two sites (Varah, 2015). The economic implications of pest control and pollination in silvoarable systems have yet to be assessed.

4.2 A proposed framework for future research

Agroforestry research in general is constrained by the suitability of appropriately scaled field sites designed for experimental vigour with proper controls (Stamps and Linit, 1999), which poses unique challenges to evaluating the factors which influence variation in effects. We therefore propose a framework to predict how these factors influence the observed abundances of natural enemies, pests and pollinators in temperate silvoarable systems (Fig. 4). For each identified factor which could influence variation, we refer to evidence from the studies included in our analysis and, as these are limited, ecological theory and evidence from analogous systems, where available, to form a series of hypotheses which can be tested by future research.

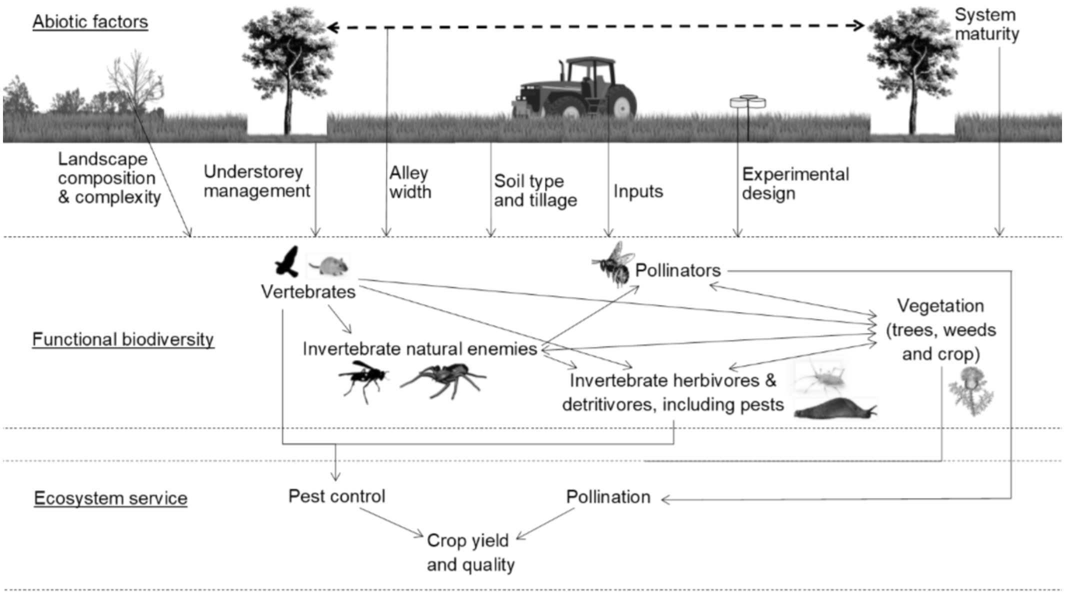

Fig. 4. Illustrative summary of the key factors predicted to influence functional biodiversity in temperate silvoarable systems, the major interactions between functional groups and their contribution to pest control and pollination.

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 in organic silvoarable systems compared with arable controls could reduce crop loss to pests. These hypotheses warrant further investigation.

4.2.3 Alley width

Alley width is typically constrained by the size of machinery in temperate regions. Although there is a strong bias in the literature towards systems with alley widths of around 12 m (Fig. 2b), three studies included in our analysis found that tree rows or the edges of crop alleys support greater abundances of natural enemies and lower pest abundances than the centre of crop alleys (Peng et al., 1993; Phillips et al., 1994; Rekany, 2015). Furthermore, stronger distribution patterns of predators have been observed in 50 m crop alleys compared with 24 m alleys (Rekany, 2015). This broadly corresponds to studies of woody field boundaries, which find highest abundances of natural enemies and pollinators at around 2 to 10 m from the boundary, before rapidly declining (Lewis, 1969; Morandin et al., 2014). Future research could therefore test whether narrow alley widths have the greatest benefit on pollination and natural enemy activity.

4.2.4 Understorey management

Two of the studies included in our analysis compared vegetated understoreys with chemically weeded understoreys. A study of aphid natural enemies found no effect between treatments, possibly because the vegetated treatment did not properly establish (Smits et al., 2012). However, Burgess et al. (2003) found fewer slugs and more spiders in alleys adjacent to vegetated versus bare understoreys, suggesting that understorey vegetation promotes pest control, although there was little difference in carabid beetle abundance between treatments. Nevertheless, management of silvoarable tree rows to promote tussock-forming grasses could replicate the benefits of beetle banks (Collins et al., 2003), which is worthy of further investigation.

In addition, evidence from flower strips shows that mixes rich in pollen and nectar are most beneficial to pollinators, whilst natural enemies appear to be less strongly associated with vegetation type (reviewed in Haaland et al. (2011)). Nevertheless, flower strips designed to benefit natural enemies of wheat pests have been successful in reducing pest pressure (Tschumi et al., 2015). A similar tailored approach could be investigated in silvoarable systems.

4.2.5 Maturity

The longest-running study in our analysis found that the slug population increased over the course of four years in a young silvoarable system compared with a control plot (Griffiths et al., 1998), whilst the abundance and/or diversity of birds and small mammals has also been shown to increase with system maturity (Gibbs et al., 2016; Klaa et al., 2005). Conversely, the abundance and diversity of epigeal invertebrate predators showed no significant response to field margin and hedgerow age in the UK, suggesting rapid colonisation, although some species were more closely associated with mature habitat (Pywell et al., 2005). We recommend that this could be investigated through long-term studies of invertebrate communities in silvoarable systems.

4.2.6 Vegetation

Two of the studies included in our analysis considered diversity and abundance of vascular plants in silvoarable versus arable systems, finding higher plant species richness in silvoarable alleys (Varah, 2015) and greater cover of non-crop plants, especially adjacent to vegetated understoreys, possibly due to seed-spread during cutting (Burgess et al., 2003). In contrast, lower numbers of weeds were found in a silvoarable system in France relative to an arable control early in the season, despite a higher species richness in the silvoarable system (Meziere et al., 2016). This contrast among studies could be explained by the differing abilities of weed species to ingress from perennial habitats (Marshall, 2004). Therefore, we would predict that weed problems in silvoarable systems will be highly context-dependent. Weed cover could also provide a mechanism for the observed benefits on natural enemies and pollinators in silvoarable systems, as demonstrated by a positive association of carabid beetle activity with weed cover in one of the studies in our analysis (Sharman, 2015).

The choice of tree species could influence micro-climatic conditions and provide resources such as nectar for functional groups. Studies of hedgerows and agroecosystems generally show that plant diversity enhances natural pest control and pollination services (Garratt et al., 2017; Isbell et al., 2017; Letourneau et al., 2011), and we would predict this to apply to silvoarable systems. On the contrary however, interplanting shrubs within apple tree rows did not influence pest or natural enemy communities in one silvoarable system (Kranz et al., 2018), although confirmatory evidence is needed from other systems to improve our understanding of the influence of tree species and diversity on pest control and pollination.

The choice of arable crop may also influence results, for example, the study with the weakest effect size for pollinators was of a pea crop, possibly because of the attractant effect of the mass-flowering resource in the control plot compared with studies based on cereal crops. Long-term and/or multiple-site studies would further test this hypothesis.

4.2.7 Trophic interactions among fauna

In general, the efficacy of conservation biological control is dependent on synergistic or antagonistic interactions between natural enemies (Straub et al., 2008; Thies et al., 2011), whilst predation of pollinators could reduce fruit set (Dukas, 2005). Few studies in our analysis considered these interactions, although positive correlations have been demonstrated between spiders and carabid beetles in a North American silvoarable system, suggesting limited interference (Stamps et al., 2009b).

Interactions between vertebrates and invertebrates could also play a role in pest control and pollination, particularly given the potential benefits of silvoarable systems on vertebrate populations. A literature search on vertebrates in temperate silvoarable systems yielded four additional studies (Supplementary Material 2), which reported increased abundance and/or species richness of small mammals (Klaa et al., 2005; Wright, 1994), bats (Disca, 2003) and birds (Gibbs et al., 2016; Williams et al., 1995). Vertebrates could benefit pest control through direct predation of pests (e.g. Kunz et al. (2011); Whelan et al. (2008)). On the other hand, vertebrates could directly cause pest problems, for example crop damage arising from roe deer, rabbits, wild boar and pigeons have been anecdotally reported in silvoarable systems (Gosme, 2014; Newman et al., 2018; Smith et al., 2016). Vertebrates could also disrupt natural enemy functionality (Martin et al., 2013), for example, an apparent increase in rats correlated with a substantial decrease in carabid beetle abundance in a silvoarable system (Stamps et al., 2009b). Interactions are therefore an important avenue for further research given their implications for pest control and potentially pollination.

4.2.8 Landscape composition and complexity

Two of the studies included in our analysis identified that proximity to treed landscape features (forestry plots or boundary hedgerows) outside of the silvoarable system influenced their results, benefitting pest parasitism and pollinator abundance respectively (Muhammad et al., 2005; Varah, 2015). The study with the second-lowest calculated effect size of natural enemy abundance noted that the diversity of the surrounding landscape may have masked any benefit of the silvoarable system (Smits et al., 2012), whilst a well-studied system in an intensive agricultural landscape had relatively strong effect sizes for natural enemies and pollinators (Rekany, 2015; Sharman, 2015; Varah, 2015). This is supported by landscape-scale studies of pest control and pollination, which suggest that functionality is high in diverse landscapes (Holzschuh et al., 2007), such that field-scale enhancements are more likely to be effective in simple landscapes, defined as 1-20% of non-crop habitat (Tscharntke et al., 2005). Although this hypothesis would be difficult to vigorously test in silvoarable systems, a standardised experimental design across a network of sites with similar characteristics but differing landscape context would help to predict those landscapes in which silvoarable systems would be most effective in terms of natural pest control and pollination.

4.2.9 Experimental design

Our results show that effect sizes in silvoarable systems tend to be relatively small compared with landscape-scale studies, and so experiments should be designed to have sufficient power to detect effect sizes of 10 to 30 % (Fig. 3). Experimental design and analysis should take limitations of survey techniques into account, for example, the inclusion of pitfall trap data collected from tree rows with complex understoreys in comparisons between silvoarable and arable systems could bias results against silvoarable systems (Thomas et al., 2006), as indicated by our analysis (Supplementary Material 3). Differences between the silvoarable and arable control plots could also influence results, particularly differences in historical land use, environmental conditions (including soil type), crop selection, management, proximity to landscape features and proximity between treatment and control plots.

4.3 Study limitations

Our analysis of pests, natural enemies and pollinators focusses on invertebrates, as other taxa have been scarcely studied in temperate silvoarable systems and predicting their net effect on pest control and pollination is often more complex than for most invertebrates. Nevertheless, we consider plants and vertebrates and their potential implications for pest control and pollination in our predictive framework above.

Pests of the arable crop component of silvoarable systems are the focus of the study, rather than pests of the tree component which have been scarcely studied. Nevertheless, there is some evidence that aphid densities are lower in silvoarable tree rows than in forestry controls (Naeem and Compton, 2000; Naeem et al., 1997). Two studies have referred to pest damage in silvoarable apple trees compared with orchards, although results are inconclusive and appear to vary according to pest taxa and fruit stage (Kranz et al., 2018; Smith et al., 2014).

Our analysis pools together numbers of captures/observations for different taxa recorded in each study, therefore, numerically abundant species are well represented in effect sizes compared with less abundant species, regardless of their body size or effect on pest control or pollination. Given that small sized carabid beetles were trapped at higher abundance in silvoarable compared with arable systems, in contrast to large generalist species (Rekany, 2015), accounting for body size could reduce effect sizes, although the situation is complex as larger carabid species could also predate smaller carabids (e.g. Prasad and Snyder (2006)), thereby antagonising pest control.

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

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

5 Conclusion

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

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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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