

Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system

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1 **Title page**

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3 Title: Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable
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6 Revision 2

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22 **Abstract**

23 The uptake of diversified farming systems is constrained by a scarcity of evidence regarding
24 financial costs, benefits, and risks. Here, we evaluate the productivity and projected farm
25 income of an agroforestry system, where apples are integrated with arable crops, by
26 combining primary data with ecosystem service and cost-benefit models. Our ecosystem
27 service assessments included: 1) weed and pest associations with arable yields; 2) apple seed
28 set as a proxy for pollination, and; 3) carbon sequestration. Arable yields were up to 11% lower
29 in agroforestry than arable systems, and were significantly negatively associated with weed
30 cover in both systems. Apple yields in agroforestry were similar to typical yields from
31 comparable orchards. Apple seed set was significantly higher in agroforestry than
32 conventional orchards for one of two varieties. Predicted gross mixed income was higher in
33 agroforestry than arable systems in 15 of 18 productivity scenarios over 20 years, which was
34 supported by a case-study. Apple yield and price were the major determinants of gross mixed
35 income. Payments for carbon sequestration were predicted to contribute 47% to 88% of
36 agroforestry establishment costs. This study demonstrates how a diversified farming system
37 can improve farm income, but grant support would reduce the initial negative cash-flow.

38 **Keywords:** cost-benefit analysis, diversified farming system, ecological intensification,
39 ecosystem services, Farm-SAFE, silvoarable

40 **1 Introduction**

41 Diversified farming systems have been proposed as a potential means of reducing the
42 environmental harm of agriculture without compromising productivity, through sustainable, or
43 ecological, intensification (Kremen and Miles, 2012; Rosa-Schleich et al., 2019). Despite this,
44 the promotion and adoption of diversified farming systems have seen limited uptake in
45 temperate regions, which is thought to be in part due to a scarcity of evidence regarding the
46 financial costs, benefits and risks relative to conventional non-diversified farming (Kleijn et al.,
47 2019; Rosa-Schleich et al., 2019). Therefore, comparative cost-benefit analyses of these

48 systems at relevant spatial and temporal scales are needed to inform policy and stimulate
49 uptake.

50 Agroforestry is a diversified farming system which involves the intentional integration of
51 productive trees or shrubs into agricultural land. Relative to monocultures, agroforestry
52 systems can enhance biodiversity and multiple ecosystem functions and services (Smith et
53 al., 2013; Torralba et al., 2016; e.g. Tsonkova et al., 2012; Udawatta et al., 2019). These
54 include marketable services such as natural pest control, pollination, and carbon sequestration
55 (De Stefano and Jacobson, 2018; Pumariño et al., 2015; Staton et al., 2019), but also
56 disservices such as higher abundances of some pest taxa (Staton et al., 2021, 2019). The
57 relative benefits and costs of these services and disservices to productivity and farm income
58 are not clear.

59 Farmers, landowners and other stakeholders perceive environmental factors such as
60 biodiversity and soil conservation as positive aspects of agroforestry systems in temperate
61 regions, while cashflow and management costs are seen as negative factors (García de Jalón
62 et al., 2018; Valdivia et al., 2012). A lower proportion of farmers in northern Europe compared
63 with the south have a positive perception of the profitability of silvoarable systems
64 (agroforestry in arable settings) (Graves et al., 2008). A survey of farmer perceptions in the
65 UK towards a poplar silvoarable system reported that although most had negative perceptions
66 of its profitability, and there was concern that tree rows could become sources of pests and
67 weeds, 20% would adopt this system if convinced of its higher profitability compared with
68 conventional arable production (Graves et al., 2017). Furthermore, a recent survey of readers
69 of the UK's Agroforestry Handbook identified a need for financial modelling of agroforestry
70 systems (Raskin, 2020).

71 Economic modelling of silvoarable systems has a long history (reviewed in Graves et al.,
72 2005). More recently, the Farm-SAFE economic model, primarily intended for timber
73 silvoarable systems, was developed under the Silvoarable Agroforestry for Europe (SAFE)
74 project (Graves et al., 2011, 2007). This model facilitated a series of studies which aimed to

75 evaluate the economic performance of silvoarable relative to arable systems in Europe and
76 Canada. These studies consistently concluded that the farm business profitability of timber
77 silvoarable relative to arable systems was dependent on high value timber trees such as
78 walnut, high timber prices, grant support, or low discount rates (Graves et al., 2007; Palma et
79 al., 2007b; Sereke et al., 2015; Toor et al., 2012; Van Vooren et al., 2016).

80 Ecosystem service valuations are widely used to demonstrate the added value of
81 environmental benefits of diversified farming systems such as agroforestry. According to
82 recent modelling studies, agroforestry systems can theoretically be more profitable than
83 conventional alternatives after accounting for payments for ecosystem services (or reductions
84 in disservices), including carbon sequestration, reduced greenhouse gas emissions, reduced
85 loss of nutrients and soils, higher groundwater recharge, and reduced pollination deficit
86 (García de Jalón et al., 2017; Giannitsopoulos et al., 2020; Kay et al., 2019).

87 Nevertheless, cashflow remains a major constraint associated with timber silvoarable
88 systems, because of the time taken for trees to reach harvest, which even for the fastest
89 growing trees is expected to be 20 years (Graves et al., 2007). Furthermore, timber trees might
90 not be eligible for agricultural subsidies and could be subject to legislative requirements for
91 replanting after harvest. These constraints are particularly pertinent to farmers on short-term
92 tenancies, which are especially prevalent in Europe. For example, between 32% and 74% of
93 agricultural land is tenanted in the UK, Germany, and France, with an average tenancy of
94 between 5 and 11.5 years (Ciaian et al., 2012), which is not feasible for timber production.

95 An alternative form of silvoarable agroforestry is orchard intercropping, where fruit trees such
96 as apple are integrated into arable or pasture (Bhardwaj et al., 2017). Although these systems
97 have historic origins, they have been gaining renewed attention recently as an alternative to
98 timber silvoarable systems, because of their potential to deliver a more rapid return on
99 investment (Gao et al., 2013; Newman et al., 2018; Smith et al., 2016). One innovative
100 example of this system comprises intercropping arable crops with apple trees on appropriate
101 rootstocks (e.g. MM106) to limit their height and subsequent shading impacts on the arable

102 crop, while being reasonably competitive with surrounding ground vegetation. Late-fruiting
103 varieties are selected so that the apple and arable harvests are temporally separated.
104 Typically, single rows of apple trees are intercropped with arable alleys, which are in most
105 cases 24 m wide to facilitate access by modern farm machinery. There has been increasing
106 uptake of this agroforestry system in recent years, particularly in the UK (Newman et al., 2018),
107 despite any studies of its financial performance.

108 In this study, we aimed to evaluate the productivity, gross mixed income, and contribution of
109 marketable ecosystem services and disservices in this apple-arable agroforestry system,
110 relative to conventional arable systems that consist of a yearly rotation of crops in
111 monoculture. We selected three ecosystem services / disservices based on the availability of
112 empirical data and/or existing models, comprising (i) arable pest and weed pressure, which
113 has been identified as a potential cost of agroforestry by UK arable farmers (Graves et al.,
114 2017); (ii) pollination, which is important for the quality and quantity of apples produced, for
115 example in the absence of pollination, apple yield is reduced by around 55 to 60 % (Garratt et
116 al., 2014; Webber et al., 2020); (iii) carbon sequestration and reduced emissions. We
117 combined primary data collection with a series of ecosystem service and cost-benefit analysis
118 models to explore the following research questions:

- 119 1. Does arable crop yield differ between the agroforestry system and arable controls, and
120 is this associated with invertebrate pest abundance and weed cover?
- 121 2. How does apple yield in the agroforestry system compare to typical orchard yields, and
122 does apple pollination differ between agroforestry and orchard systems?
- 123 3. What is the value of carbon sequestration and reduced emissions in the agroforestry
124 system compared with the arable controls?
- 125 4. Theoretically, how does gross mixed income of the agroforestry system compare with
126 arable controls, how does empirical case-study data compare to these theoretical
127 expectations (cost-effectiveness analyses), and which factors most strongly influence
128 gross mixed income (sensitivity analysis)?

129

130 **2 Methods**131 *2.1 Arable yields and associations with pests and weeds (Question 1)*

132 To compare crop yields between the agroforestry and arable systems, we sampled cereal
 133 yield (scaled up to tonnes per hectare) from three UK sites (see Supplementary Material 1).

134 Each site was a working farm containing (i) an agroforestry field, configured in an alley-
 135 cropping arrangement where single tree rows were intercropped with 24 m wide arable crop
 136 alleys, and (ii) an arable field under the same management. Two years (i.e. two harvests) of
 137 data were collected for each site, between 2018 and 2020. The sampled cereal crops
 138 comprised winter oats (2 sites), winter wheat (2 sites) and spring barley (1 site). At each site,
 139 samples were collected from 12 points in the agroforestry field, located 0.5, 5 and 9.5 m from
 140 the tree row, and from 16 points within the arable field following the same pattern around
 141 'virtual' tree rows with additional samples at 0 m. Each grain sample was taken from a 50 x 50
 142 cm quadrat, within one week of the field harvest commencing. Samples were threshed using
 143 a Wintersteiger Hege 16 and then weighed. Models were built to test the effect of farming
 144 system (agroforestry versus arable), crop type and distance from tree row on yield (Table 1).

145 **Table 1.** Variables and data subsets used to build linear models, mixed models, and generalised linear
 146 mixed models. 'Farming system' refers to agroforestry versus arable/orchard. Analysis was undertaken
 147 in R version 3.5.2 (R Core Team, 2018) using the 'lme4' package (Bates et al., 2015). OLRE =
 148 observation-level random effect, to account for overdispersion.

Response	Fixed effects	Random effects	Subset	Family
Grain weight	Interaction between farming system, and crop type (barley/wheat or oats), with main effect for farming system removed	Site, year	-	Gaussian
Grain weight	Distance from tree row	Site, year	Agroforestry	Gaussian

Grain weight	Farming system, weed cover, slug abundance. Separate models to test interaction between farming system and weed cover or slug abundance.	Site, year	Slug data filtered to only include pre-harvest records.	Gaussian
Apple seed counts	Year (as factor)	Site, OLRE	Orchards, separate model for each variety	Binomial
Apple seed counts	Farming system	Site, OLRE	Separate model for each variety	Binomial
Apple seed counts	Farming system, pesticide use (binary)	Site, OLRE	Separate model for each variety	Binomial
Equivalent annual value (EAV)	Farming system	-	-	Gaussian

149

150 A previous study found higher slug abundance and non-crop plant cover in agroforestry crop
151 alleys compared with arable fields (Staton et al., 2021), using data collected from the same
152 sample locations as the yield data in this study. Therefore, to investigate possible effects on
153 yield, we tested associations between these two taxa with arable yield using mixed models
154 (Table 1).

155 2.2 *Apple pollination and yield (Question 2)*

156 We sampled apple fruits from four UK agroforestry sites in August and September 2020
157 (Supplementary Material 1). At each site, between 40 and 100 apples were sampled to record
158 maximum width and number of seeds. The number of fruits on each sampled tree was also
159 recorded, except at the Norfolk site where the apples had already been harvested. We
160 sampled two varieties: Bramley (a large culinary apple) from all four sites, and Braeburn
161 (desert apples) from two sites (Supplementary Material 1). An equal number of Bramley and
162 Braeburn were sampled at the latter two sites.

163 We estimated apple yield at each site based on the number of apples per tree and predicted
164 apple weight, derived from the relationship between width and weight for both varieties in

165 Garratt et al. (2016b) (Supplementary Material 2). Predicted yields were compared to expected
166 yields in the Organic Farm Management Handbook (Lampkin et al., 2017), because none of
167 the apples in the agroforestry sites were treated with pesticides.

168 Seed counts per apple are a proxy for pollination service (Garratt et al., 2016a; Webber et al.,
169 2020). Therefore, to compare pollination service, the seed set per apple from the agroforestry
170 sites was compared to previously published orchard data in Garratt et al. (2016b). To compare
171 this orchard dataset to 2020 conditions, we sourced 30 each of non-organic and organic
172 Bramley, 40 non-organic Braeburn and 40 organic Braeburn apples from a wholesaler. These
173 originated from orchards in Kent, UK, however no UK source was available for organic
174 Braeburn, so this was sourced from Lower Saxony, Germany, which is climatically very similar
175 to Kent. Maximum width and number of seeds were measured in these fruits.

176 The effect of year on seed count in orchard apples was tested using binomial GLMMs for each
177 variety (Table 1). Year had no significant effect (Supplementary Material 3); therefore, 2016
178 and 2020 data were combined to test the effect of farming system (agroforestry versus orchard
179 systems) on seed counts for each variety (Table 1). We also ran a separate model with
180 pesticide use (organic/no-spray or conventional) as an additional fixed effect, although only
181 one organic orchard site was available for each variety.

182 The value of pollination was estimated using formulae adapted from Garratt et al. (2014)
183 (Supplementary Material 2), which compares pollination value between two treatments (in this
184 case agroforestry versus orchard systems) based on differences in fruit set and weight. To
185 control for confounding factors which could affect apple fruit set, weight and width, such as
186 soil type, climate and management, only seed count data was used as empirical data input.
187 Apple width, weight and fruit set were estimated using their relationships with seed count,
188 based on the data in Garratt et al. (2016b) for each variety.

189 *2.3 Carbon emissions and sequestration (Question 3)*

190 To predict carbon dioxide emissions and sequestration, we primarily used the Farm Carbon
191 Calculator (Farm Carbon Toolkit, 2020), which is a web-based carbon calculator, underpinned
192 by peer-reviewed evidence, designed to assess emissions and sequestration on UK farms.
193 We focussed on two factors: emissions from crop residues and sequestration from fruit trees.
194 We took a conservative approach by not incorporating other factors such as machinery
195 movements and inputs, because although these are likely to be reduced in the agroforestry
196 system, there is uncertainty depending on management of the tree rows. Soil carbon stocks
197 vary little between agroforestry and arable systems, according to recent modelling, so were
198 not included here (Giannitsopoulos et al., 2020).

199 Reduction in emissions from crop residues depends on crop type and yield, so was modelled
200 separately for each of three productivity levels (low, average and high, described further in
201 Section 2.4.1), management system (conventional or organic) and crop type. Sequestration
202 from fruit trees was based on the area they occupy (9.2%) in the modelled agroforestry system
203 described at Section 2.4. The amount of carbon dioxide sequestered by apple trees, including
204 below-ground sequestration, was assumed to be 3.3 or 5.0 t CO₂e/ha/year (Farm Carbon
205 Toolkit, 2020; Page, 2011).

206 For each productivity scenario, we calculated the net difference in greenhouse gas
207 emissions/sequestration, i.e. emissions in arable minus agroforestry systems, plus
208 sequestration in the agroforestry system. Two scenarios for greenhouse gas (CO₂e) values
209 were evaluated: (i) traded EU allowances, which reflect current and projected trading prices,
210 and (ii) non-traded shadow price of carbon. The latter incorporates discounted future social
211 costs of greenhouse gas emissions and can be interpreted as the government's willingness to
212 pay for reductions in carbon emissions. Carbon prices were sourced from the UK's Green
213 Book Supplementary Guidance (Department for Business, Energy & Industrial Strategy, 2019)
214 and covered the period 2020 to 2039 to reflect predicted increases in carbon value over the
215 next 20 years.

216 *2.4 Gross Mixed Income (Question 4)*

217 Financial cash-flow was quantified as gross mixed income (GMI), because this represents the
 218 most relevant outcome for small family businesses by representing joint income from their
 219 unpaid labour and capital investments, unlike profit which deducts all labour costs and is more
 220 relevant to corporations. The most established field site from which we collected empirical
 221 arable and apple data was used as a model system to investigate farm income (i.e. GMI) and
 222 the contribution of marketable ecosystem services, relative to an equivalent arable system.
 223 This site was Whitehall Farm, Cambridgeshire, UK (described in Newman et al. (2018)), where
 224 an agroforestry system was planted across approximately half of the farm (52 ha) in 2009,
 225 with the remainder retained as monoculture arable land. The modelled agroforestry system
 226 and arable controls were based on a theoretical 16 ha field (Supplementary Material 4), which
 227 is the average field size in Cambridgeshire, where over 80% of farmed land is arable
 228 (Robinson and Sutherland, 2002). We analysed economic performance over a 20 year period,
 229 because this is the typical duration of dessert apple trees (Redman, 2017).

230 To compare the financial performance of the agroforestry system compared with arable
 231 controls, we used the xlwings library in Python version 3.7.4 (Python Software Foundation,
 232 2019) to manipulate inputs into the Excel-based Farm-SAFE economic model (Graves et al.,
 233 2011, 2007). Model outputs were similarly extracted with Python and plotted using the 'ggplot2'
 234 package in R version 3.5.2 (R Core Team, 2018; Wickham, 2016). The current value of future
 235 GMI was calculated as net present value (NPV, Equation 1), by reducing costs and benefits
 236 that occur in future years (Equation 2) by an annual discount rate, which was set at 3.5% (HM
 237 Treasury, 2018).

$$238 \quad (1) \quad NPV = \sum_{y=1}^n \left(\frac{GMI_y}{(1+r)^y} \right) - i$$

239 Where GMI = annual gross mixed income (Equation 2), i = capital investment costs based on
 240 scaled costs of orchard establishment (see Supplementary Material 6), n = total number of
 241 years (20, which is the typical duration of dessert apples (Redman, 2017)), r = discount rate
 242 (3.5%), and y = year after present (year 0).

243 (2) $GMI = (yield \times price) + subsidies - variable\ costs - fixed\ costs$

244 In Equation 2, yield and price represent both the apple and arable components of the system
 245 (explained in Sections 2.4.1 and 2.4.2). Apple yields were reduced in the first five years to
 246 account for establishment. Subsidies comprised Basic Payment Scheme plus greening, plus
 247 Countryside Stewardship organic payments for organic systems, and were equivalent for the
 248 agroforestry and arable systems (except for the case study, explained at Section 2.4.2).
 249 Variable costs included seed, fertiliser, sprays, and casual labour, plus annual pruning and
 250 harvesting of apple trees and removal of apple trees in year 20. Fixed costs included paid and
 251 casual labour, machinery, overheads, and rent. Further information on these parameters is
 252 provided in Supplementary Material 6.

253 We also calculated equivalent annual value (EAV, Equation 3), which represents NPV in
 254 annual terms (parameters are defined in Equation 1):

255 (3) $EAV = \frac{NPV \times r}{1 - (1 + r)^{-n}}$

256 All analyses used Euro currency for consistency with the Farm-SAFE model and previous
 257 associated publications, using an exchange rate of £1 = €1.18 based on the Bank of England's
 258 spot exchange rate for the end of 2019 (Bank of England, 2020). Outputs are converted to
 259 pound sterling in Supplementary Material 5.

260 2.4.1 Theoretical GMI

261 We tested the theoretical GMI of the agroforestry versus arable systems using farm
 262 management handbooks, which provide cost, yield and price figures for low, average and high
 263 levels of production, reflecting farm-dependent factors such as soils, climate and farmer
 264 expertise (Lampkin et al., 2017; Redman, 2017). As the productivity level of combinable crops
 265 is not necessarily related to the apple crop, we modelled each combination of productivity
 266 level, for each management system (conventional versus organic). Therefore, 18 productivity
 267 scenarios were modelled (3 combinable crop yield levels x 3 apple yield levels x 2

268 management systems). In each scenario, the financial performance (NPV and EAV) of the
269 agroforestry system was compared with the equivalent arable system.

270 Apple harvest costs (e.g. harvesting and packing, see Supplementary Material 6) were
271 calculated per tonne of harvested apples. Otherwise, all parameters other than yield remained
272 constant among productivity levels (Supplementary Material 6). The modelled conventional
273 system was based on rotation of two years of winter wheat followed by a third year of oilseed
274 rape (OSR). This is a widely used crop rotation in Europe, for example, OSR covered 380,000
275 hectares in the UK in 2020 (Defra, 2020), suggesting that this rotation occupies approximately
276 1 million hectares in the UK (assuming OSR recurs every three years). The modelled organic
277 system comprised a six-year rotation of red clover, winter wheat, winter oats, spring beans,
278 winter triticale, and spring barley, which has been recommended as a balanced rotation in the
279 UK (HGCA, 2008). In all cases, the crops grown in comparable agroforestry and arable
280 systems were the same, so that only the presence of agroforestry tree rows and the area
281 occupied by combinable crops differed between the two systems.

282 2.4.2 Case study

283 Annual records of apple and combinable crop yields in the agroforestry and arable fields,
284 collected by the farm manager at the Whitehall Farm site, were used to empirically test the
285 GMI of the agroforestry versus arable systems. Because different fields within the farm are at
286 different stages of rotation, we ran 1000 Monte Carlo simulations, with the crop rotation in
287 each simulation randomised based on the proportion of crops in the actual rotation
288 (Supplementary Material 7). The same crop type was applied to agroforestry and arable fields
289 in each year. For each year, in each simulation, apple and combinable crop yields were
290 randomly sampled from a normal distribution based on the mean and standard deviation of
291 the empirical yield data. Equal arable yields were applied to each farming system, to reflect
292 the comparable yields between farming systems at this site. Initial establishment costs were
293 1357 €/ha, based on actual data from Whitehall Farm. Fertiliser and apple protection
294 (pesticide) costs were not included to reflect farm practices. A countryside stewardship AB8

295 grant (€636.02 per ha of trees) was included for the tree row flowering understorey, and
296 establishment costs included. Otherwise, model parameters were applied according to the
297 organic system at Supplementary Material 6. The effect of farming system on GMI
298 (represented by EAV) was tested using a linear model (Table 1).

299 2.4.3 Sensitivity analysis

300 To investigate the sensitivity of GMI in the agroforestry system, the above case study analysis
301 was run under the following scenarios (1000 simulations for each scenario): (i) low arable
302 yields, reduced by 11.4% in the agroforestry system (based on barley/wheat yields in Section
303 3.1); (ii) low apple yields, comprising the lower estimate of observed agroforestry yields (4
304 t/ha, from the Whitehall Farm case study); (iii) high apple yields, comprising the upper estimate
305 of observed agroforestry yields (14.84 t/ha, from Section 3.2); (iv) low apple prices, based on
306 100% processing (£0.2/€0.24 per kg (Lampkin et al., 2017)), to test a wholesale juicing market
307 scenario rather than eating/cooking apples; and (v) the lower and upper estimates of carbon
308 payments for the agroforestry system (based on Section 3.3).

309 3 Results

310 3.1 Cereal yields and associations with pests (Question 1)

311 Grain weight of barley or wheat was 11.4% lower in agroforestry than arable fields, which was
312 statistically significant ($t=-2.440$, $p\text{-value}=0.016$), but grain weight of organic oats did not
313 significantly differ between agroforestry and arable fields ($t=-0.087$, $p\text{-value}=0.931$). However,
314 crop type was confounded with year, site and organic management, therefore differences in
315 effects between crop types should be treated with caution. Yield of the pooled crop data was
316 17.2% higher at the centre of the alleys than at 0.5 m from tree rows, but this was not
317 significant ($t=1.796$, $p=0.077$).

318 Cereal yield was significantly negatively associated with weed cover ($t=-3.045$,
319 $p\text{-value}=0.003$), but was not significantly associated with slug abundance ($t=-1.798$, p -

320 value=0.076). There was no significant interaction between farming system and either weed
321 cover or slug abundance (Supplementary Material 3).

322 3.2 *Apple pollination and yield (Question 2)*

323 Estimated yields of agroforestry-grown apples ranged from 5.677 to 14.835 tonnes per ha of
324 apples (Table 2). These values are comparable to expected yields from young organic
325 orchards which typically yield 3 t/ha for years 1-5 and 16 t/ha for years 6-11 (Lampkin et al.,
326 2017). Approximately 70% of Braeburn were of sufficient width for Grade 1 or 2 (Table 2),
327 comparing closely with expectations for organic orchards (Lampkin et al., 2017).

328 **Table 2.** Estimated apple yields (per hectare of apples) at agroforestry sites, calculated based on the
329 number of apples per tree and apple width. Grade 1/2 is based on maximum width of at least 60 mm.
330 Apples per tree and yield could not be obtained from the Norfolk site because the apples were harvested
331 prior to sampling.

Site	Variety	Year of trees	Percentage grade 1/2	Mean apples per tree	Mean estimated weight per apple (g)	Estimated yield (t/ha, all grades)
Nottinghamshire	Braeburn	7	68.7	48.7	104.74	5.677
Nottinghamshire	Bramley	7	100	69.8	191.19	14.835
Oxfordshire	Bramley	6	100	27.6	219.64	6.735
Cambridgeshire	Bramley	11	99	40.8	205.54	9.325
Norfolk	Braeburn	4	70	-	108.80	-
Norfolk	Bramley	4	99	-	184.46	-

332

333 Seed set in Bramley apple was significantly higher in four agroforestry sites than five orchard
334 sites (mean 4.05 in agroforestry vs. 2.61 in orchards, $z=2.108$, $p\text{-value}=0.035$), indicating a
335 higher level of pollination in the agroforestry system. This was however not significant when
336 pesticide application on apples was included as a binary fixed effect ($z=-1.110$, $p\text{-}$
337 $\text{value}=0.267$), although only one organic orchard site and no agroforestry sites with apple

338 pesticide use were available. Seed set for Braeburn was not significantly different between
 339 two agroforestry and four orchard sites ($z=-0.286$, $p\text{-value}=0.775$), providing no evidence for
 340 a difference in pollination service. The value of pollination service in agroforestry-grown
 341 apples, relative to orchards, depended on variety and organic management, ranging from
 342 104.08 €/ha compared with conventional Bramley orchards to -28.99 €/ha compared with
 343 organic Braeburn (Table 3).

344 **Table 3.** Value of pollination (€/ha/year of agroforestry) in no-spray agroforestry-grown apples,
 345 compared with orchards, using seed counts to predict apple weight, grading and fruit set. Positive
 346 values represent higher pollination value in agroforestry than orchard systems.

Apple production level	Value of apple pollination in agroforestry compared with:			
	Conventional		Organic	
	Bramley orchard	Braeburn orchard [†]	Bramley orchard* [†]	Braeburn orchard* [†]
Low	45.51	30.95	-1.81	-2.23
Average	74.80	50.86	-14.47	-17.84
High	104.08	70.78	-23.52	-28.99

347 * Only one site was available

348 [†] difference in seed counts between agroforestry and orchard systems was not significant

349 3.3 Added value from carbon sequestration / reduced emissions (Question 3)

350 The net reduction in carbon dioxide emissions in agroforestry compared with equivalent arable
 351 systems ranged from 312.9 to 552.4 kg CO₂e/ha/year (Table 4). The main contributor to this
 352 reduction, and determinant of variation therein, was carbon sequestration by apple trees.
 353 Using predicted market prices of carbon over the next 20 years, the equivalent annual value
 354 (EAV) of net carbon emission reductions in the agroforestry compared with arable systems
 355 ranged from 44.96 to 49.57 €/ha for the lower estimate of fruit tree sequestration, to 65.54 to
 356 70.15 €/ha for the upper sequestration estimate (Table 5). Using non-market shadow price of
 357 carbon, these figures increased to 53.71 to 59.12 €/ha, and 78.26 to 83.66 €/ha (Table 5), for
 358 lower and upper sequestration estimates respectively.

359 **Table 4.** Modelled greenhouse gas (GHG) emission reductions and sequestration in the agroforestry
 360 versus equivalent arable systems. Ranges are given for reduction emissions as these depend on the
 361 crop stage of the rotation, and the range for fruit tree sequestration represents data from different
 362 studies.

System	Production level	Reduction in emissions from crop residues (kg CO ₂ e/ha/year)	Sequestration from fruit trees (kg CO ₂ e/ha/ year)	Net change in GHG (kg CO ₂ e/ha/year)
Conventional	Low	39.2 to 59.4	303.4 to 460.0	342.8 to 519.4
	Average	45.8 to 70.3		349.4 to 530.3
	High	52.3 to 81.9		355.9 to 541.9
Organic	Low	9.3 to 92.4		312.9 to 552.4
	Average	9.9 to 92.4		313.5 to 552.4
	High	1.2 to 92.4		315.3 to 552.4

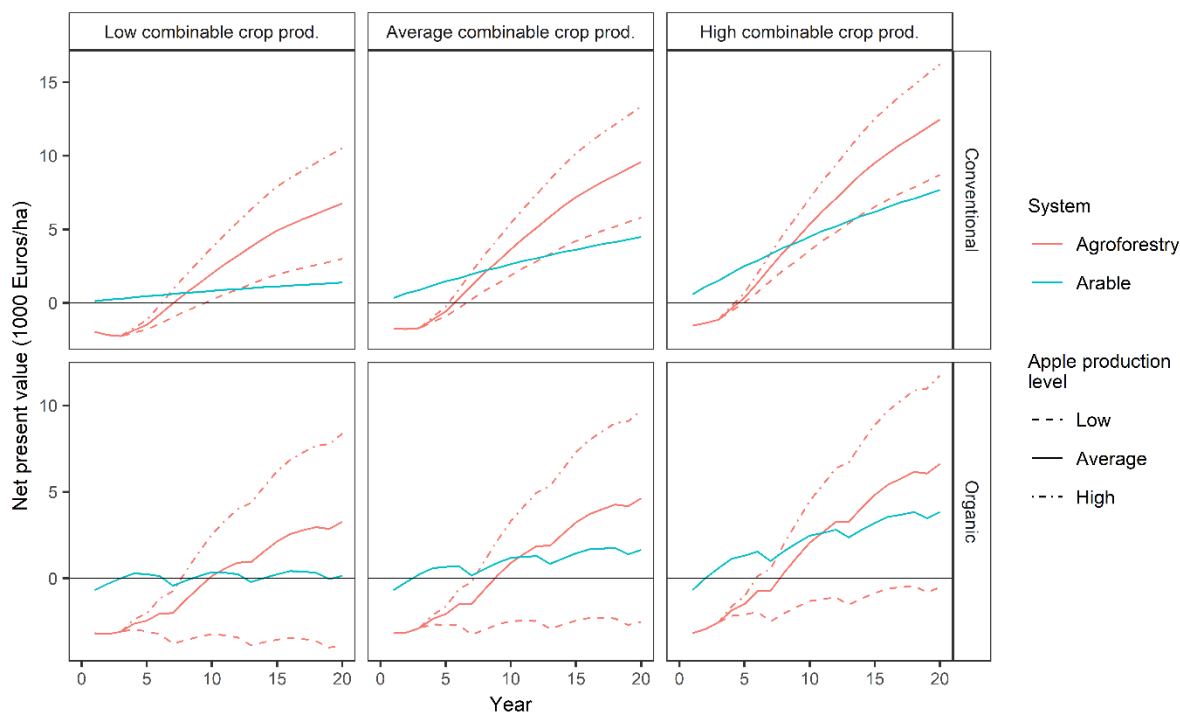
363

364 3.4 Gross Mixed Income of the agroforestry system (Question 4)

365 3.4.1 Theoretical Gross Mixed Income

366 Modelling predicted that the agroforestry system was initially at negative cash-flow, arising
 367 from establishment costs and the time-lag before apples became productive. By the end of
 368 the 20-year simulation however, gross mixed income (GMI), represented by net present value
 369 (NPV) and equivalent annual value (EAV), in agroforestry was higher than for the equivalent
 370 arable systems in 15 of the 18 modelled scenarios (Fig. 1, Table 5). Of these 15, NPV in
 371 agroforestry exceeded the equivalent arable scenario after seven to 14 years (Table 5). The
 372 three agroforestry scenarios with lower GMI than arable systems were all organic systems
 373 with low apple productivity. In these scenarios, GMI (expressed as EAV) of the agroforestry
 374 system remained lower than for the equivalent arable system even without establishment
 375 costs.

376



377

378 **Figure 1.** Modelled cumulative gross mixed income (expressed as net present value) of agroforestry
 379 versus arable systems over a 20-year system lifespan. Each column represents a combinable crop
 380 productivity level, whilst the rows represent conventional or organic management.

381

382 **Table 5.** Economic performance of agroforestry (AF) compared with equivalent arable systems, under
 383 18 different scenarios of management regime, arable crop productivity level (PL) and apple productivity
 384 level (as defined by farm management handbooks). Cumulative gross mixed income is represented by
 385 net present value (NPV), whilst equivalent annual value (EAV) is the equivalent annual value for a 20-
 386 year system lifespan. All financial values (NPV/EAV) are expressed as €/ha.

Scenario			Years for	Arable	AF EAV	AF EAV	Carbon	Carbon
Inputs	Arable	Apple	AF NPV to	EAV	with	without	EAV	EAV
	PL	PL	exceed		establishme	establishme	(market	(shadow
			arable NPV		nt costs	nt costs	price)	price)
Conventi onal	Low	Low	12	97.01	210.35	352.20	46.97 –	56.02 –
	Low	Average	9	97.01	475.23	617.07	67.56	80.57

	Low	High	7	97.01	740.10	881.95		
	Average	Low	13	315.43	408.68	550.52	48.24 –	57.54 –
	Average	Average	9	315.43	673.55	815.40	68.82	82.08
	Average	High	7	315.43	938.43	1080.27		
	High	Low	14	539.84	612.45	754.29	49.57 –	59.12 –
	High	Average	9	539.84	877.32	1019.17	70.15	83.66
	High	High	7	539.84	1142.19	1284.04		
Organic	Low	Low	Infinite	10.41	-272.74	-95.85	44.96 –	53.71 –
	Low	Average	11	10.41	230.09	406.99	65.54	78.26
	Low	High	8	10.41	589.26	766.15		
	Average	Low	Infinite	115.92	-176.94	-0.04	45.41 –	54.24 –
	Average	Average	11	115.92	325.90	502.79	65.99	78.79
	Average	High	8	115.92	685.06	861.96		
	High	Low	Infinite	270.47	-36.61	140.29	45.50 –	54.93 –
	High	Average	11	270.47	466.22	643.11	66.58	79.47
	High	High	8	270.47	825.39	1002.28		

387

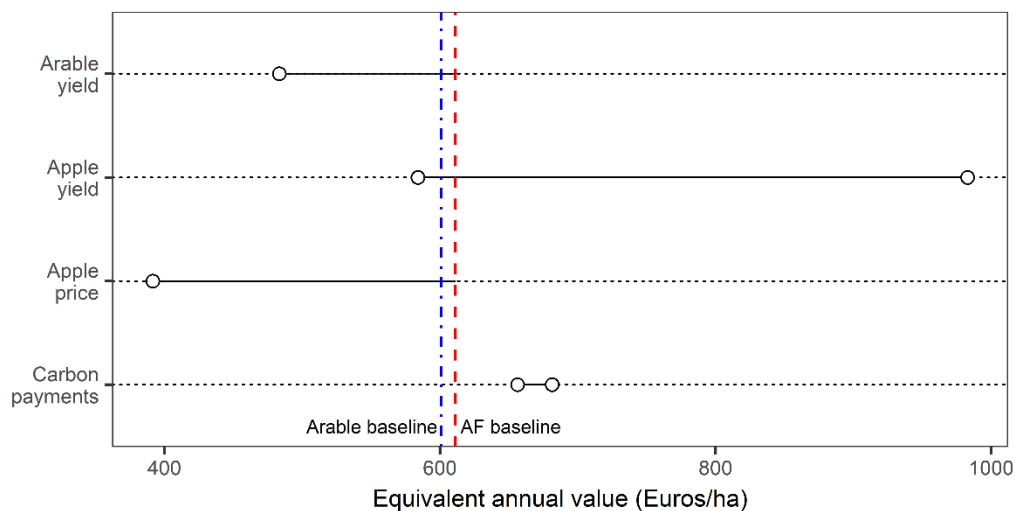
388 *3.4.2 Modelled GMI based on a case study agroforestry system*

389 Cereal yields at the case study farm were similar between agroforestry and arable fields, and
390 were similar to or higher than those stated in the Organic Farm Management Handbook for a
391 high productivity level organic farm, while apple yields were between low and medium
392 productivity levels (Lampkin et al., 2017). According to 1000 simulations using random
393 samples taken from the empirical data, the EAV of the agroforestry simulations over the 20-
394 year system lifecycle was 10.25 €/ha (8.69 £/ha) higher than the equivalent arable simulations.
395 Cumulative GMI (expressed as NPV) of the agroforestry system was higher than the arable
396 system within the 20-year lifecycle in 75.7% of cases. In those cases, the agroforestry system
397 was initially at negative cash-flow but NPV exceeded the equivalent arable system after a
398 mean of 17.79 years. This is consistent with the theoretical expectation for an organic farm
399 with high arable productivity and low to average apple productivity (Table 5).

400 3.4.3 Sensitivity analysis

401 Sensitivity analysis of the above case-study simulation identified that apple yield and price
 402 were the major factors determining GMI of the agroforestry system (Fig. 2). For example,
 403 simulations based on the upper estimate of apple yield (14.49 t/ha) increased EAV of the
 404 agroforestry system by 61% compared with the baseline scenario where mean apple yield
 405 was 4.81 t/ha. Simulations assuming wholesale processing prices for all apples (£0.2/€0.24
 406 per kg) reduced EAV by 36% compared with the baseline assumption of 70% Grade 1 or 2
 407 wholesale apples.

408



409

410 **Figure 2.** Sensitivity analysis to compare alternative scenarios for the agroforestry system. The arable
 411 and agroforestry (AF) baseline scenarios are mean equivalent annual values (EAV) from the case study
 412 simulation (Section 3.4.2). The points represent mean EAV of agroforestry under the following
 413 scenarios, with inputs manipulated in isolation: the arable yield scenario assumes 11.4% reduction in
 414 arable yield in the agroforestry system (from Section 3.1), the apple yield scenarios represent the
 415 minimum yield recorded from the case study farm (4 t/ha, excludes establishment years) and the
 416 maximum yield from an agroforestry system (Section 3.2), the low apple price scenario assumes a
 417 processing price of 0.24 €/kg for all apples (compared with 70% Class 1/2 at 1.06 €/kg for the baseline
 418 scenario), and the carbon scenarios represent grant payments for carbon sequestration (Section 3.3).

419

420 **4 Discussion**

421 In this study we (i) compared empirical arable and apple yields between agroforestry and
422 monoculture (arable/orchard) systems, (ii) evaluated the costs and benefits of weed/pest
423 pressure, apple pollination, and carbon sequestration in terms of productivity and/or gross
424 mixed income (GMI), and (iii) modelled GMI of the agroforestry versus arable systems. We
425 found 11% lower wheat/barley yields in the agroforestry than arable system, but no significant
426 effect for oat yield, while there were significant negative associations between yield and weed
427 cover. Apple yields in the agroforestry system were highly variable among sites and varieties,
428 but were consistent with expected yields in comparable orchards. Apple pollination level, as
429 indicated by seed set, was significantly higher in agroforestry-grown Bramley apples than
430 conventional orchards, but there was no significant difference after accounting for pesticide
431 use, or for Braeburn apples. Cumulative GMI of the agroforestry system was predicted to be
432 higher than that of an equivalent arable system within a 20-year lifespan, except in low
433 production, organic systems. Financial modelling of a case study system, using empirical data,
434 was consistent with theoretical predictions. A sensitivity analysis demonstrated that apple yield
435 and price were the major determinants of GMI of the agroforestry system, and were capable
436 of more than compensating for an 11% reduction in arable yield. Carbon sequestration and
437 reductions in emissions added further value to the agroforestry system.

438 *4.1 Cereal productivity*

439 Our finding of lower wheat/barley yields in the agroforestry compared with arable systems is
440 consistent with short-term yield reductions in other diversified farming systems (reviewed in
441 Rosa-Schleich et al., 2019). The 11% yield reduction compares favourably to the 10-26%
442 reductions for barley and 11-15% reductions for wheat in a timber agroforestry system with
443 12 m wide alleys (García de Jalón et al., 2017; Giannitsopoulos et al., 2020). Furthermore, in
444 that timber system, arable cropping was predicted to be unprofitable after 5 to 13 years
445 depending on alley width (Burgess et al., 2003), whereas continuous arable cropping appears
446 to be financially viable in the apple-arable agroforestry system, albeit longer-term yield

447 monitoring is needed. Our yield effects however compare less favourably to the reported 16%
448 increase in wheat yield in a short-rotation coppice system with 48 m wide alleys (Kanzler et
449 al., 2019), while another study found similar yields between short-rotation coppice systems
450 with 48 and 96 m wide alleys, and arable control fields (Swieter et al., 2019). Although the
451 effects of farming system on yield of different crop types was confounded with site and should
452 be interpreted with caution, we found comparable oat yields between the agroforestry and
453 arable systems, possibly because oats are more competitive with weeds and resistant to slug
454 damage than wheat or barley (Douglas and Tooker, 2012; Seavers and Wright, 1999).

455 We found a negative relationship between cereal yields and proximity to tree rows, although
456 the results were not statistically significant (p -value=0.77). Nevertheless, alley width is likely
457 to be an important factor when comparing yields between agroforestry and arable systems
458 (Burgess et al., 2003). For example, according to a meta-regression, tree rows and hedgerows
459 reduce yields of adjacent crops, relative to arable controls, up to a distance into the crop alley
460 of 1.64 times the tree height (Van Vooren et al., 2016), but have positive or negligible effects
461 thereafter. This translates to approximately half of the crop alley in an apple-arable
462 agroforestry system with 24 m wide alleys and MM106 rootstocks, where the trees reach
463 approximately 4 m height, which are typical choices for modern agroforestry systems.

464 Competition between trees and arable crops for resources such as water, light and nutrients
465 has been cited as the major cause of arable yield reductions in agroforestry systems (Jose et
466 al., 2004), although cultivar selection programs have potential to mitigate this (Arenas-
467 Corraliza et al., 2021). Our finding of negative associations between weed cover and yield
468 suggests that weed competition could also be a factor in organic agroforestry systems,
469 although we cannot demonstrate any causal relationship. Previous studies have shown that
470 weed cover in agroforestry versus arable systems varies among sites, possibly depending on
471 the response traits of the dominant weed species (Boinot et al., 2019; Staton et al., 2021),
472 suggesting that this potential cause of yield reduction may only apply to sites with problematic
473 creeping, perennial weeds. Similarly, slug abundance has previously been linked to pea crop

474 damage in agroforestry crop alleys (Griffiths et al., 1998). We found no significant evidence
475 for this based on spring counts, although autumn and winter slug abundance may be of more
476 relevance for winter-sown crops.

477 Despite the short-term negative effects on wheat/barley yield, yield stability is typically higher
478 in diversified farming systems compared with non-diversified systems (Rosa-Schleich et al.,
479 2019), including intercropping of annual crops (Raseduzzaman and Jensen, 2017), while
480 proximity to semi-natural habitats improves yield resistance to extreme weather events
481 (Redhead et al. 2020). Agroforestry systems could improve yield stability and climate
482 resilience by moderating the impacts of extreme weather events, such as drought and high
483 winds (Arenas-Corraliza et al., 2018; Kanzler et al., 2019), and in the longer-term, protection
484 from soil erosion (Tsonkova et al., 2012; Varah et al., 2013). Natural enemy activity has also
485 been postulated as a probable mechanism for higher yield stability with proximity to semi-
486 natural habitat (Redhead et al., 2020), and agroforestry systems increase the functional trait
487 diversity of natural enemies compared with arable monocultures (Staton et al., 2021).

488 *4.2 Apple productivity and pollination*

489 We found that apple yields in the agroforestry system strongly varied among sites, even for
490 the same variety. Possible explanations for this variation are differences in site conditions such
491 as soil type, management (e.g. pruning), alternate bearing (natural yield fluctuations between
492 years), and tree age, which varied from 6 to 11 years, the youngest of which had only just
493 entered full production. Productivity data from this novel agroforestry system are scarce,
494 although Smith et al. (2016) also found substantial variation in apple yields; depending on
495 variety and year, yields varied from 0.25 to 15.18 t/ha (of apple trees) for the 5-6 year old
496 Cambridgeshire system also used in our study, and 15.7 to 19.25 t/ha for a 18-19 year old
497 system which used MM111 rootstocks. At the Cambridgeshire site, Bramley yields of 0.35 and
498 3.71 t/ha were reported in 2014 and 2015 respectively, compared to our finding of 9.33 t/ha in
499 2020. The existing data tentatively suggests that fruit trees in agroforestry settings could take
500 longer than expected to enter full production, possibly because the understorey vegetation

501 competes for resources (Granatstein and Sanchez, 2009) and because of the more exposed
502 conditions.

503 Pollination levels in Bramley, represented by seed set, were significantly higher in the
504 agroforestry system than in conventional orchards, but preliminary findings from one organic
505 orchard suggest similar levels to the agroforestry sites. Furthermore, we found no significant
506 difference between agroforestry and orchard systems for Braeburn seedset, suggesting that
507 the comparison between agroforestry and orchard systems is complex and moderated by
508 other factors such as variety and pest management. Nevertheless, our findings suggest that
509 the more exposed conditions and lower densities of apples trees in agroforestry compared
510 with orchard systems does not substantially reduce seed set.

511 4.3 *Carbon sequestration*

512 We estimated a reduction in greenhouse gas emissions in the agroforestry compared with
513 arable systems of 312.9 to 552.4 kg CO₂e/ha/year, the majority of this (83 to 97%) being
514 attributable to sequestration by trees. This is at the lower end of the predicted range of 366 kg
515 to 11 t CO₂e/ha/year for tree sequestration over a 60-year simulation of European agroforestry
516 systems (Palma et al., 2007a). While sequestration will inevitably be lower than fast-growing
517 timber agroforestry systems (e.g. Giannitsopoulos et al., 2020), our results suggest that the
518 apple-arable agroforestry system can make a meaningful contribution to climate change
519 mitigation in agriculture, which we value at between 44.96 and 70.15 €/ha per year (equivalent
520 to net present value (NPV) of 639 to 997 €/ha) using predicted market carbon prices, or 53.71
521 and 83.66 €/ha per year (NPV of 763 to 1189 €/ha) for non-market shadow price. Given the
522 reported establishment costs of 1357 €/ha of the agroforestry system (Newman et al., 2018),
523 an upfront carbon payment would cover 47% to 73% of these costs using market prices, or
524 56% to 88% using shadow prices.

525 4.4 *Farm Income*

526 Cumulative gross mixed income (GMI) of the agroforestry system was consistently predicted
527 to be higher than of the equivalent arable systems within a 20-year system lifespan, with the
528 exception of organic systems with low apple productivity. Apple productivity and price were
529 the most important factors determining GMI of the agroforestry system, and were capable of
530 substantially outweighing an 11% reduction in cereal yield. For example, by assuming apple
531 yields were consistently at the maximum recorded in the study, equivalent annual value (EAV)
532 of GMI increased by €349 compared with the baseline agroforestry scenario, while the
533 difference between 70% Class 1 or 2 and 100% processing wholesale prices represented
534 €233 EAV. These compare to a loss of €147 EAV resulting from an 11.4 % reduction in arable
535 yields in the agroforestry system. These figures demonstrate the importance of proper
536 management and protection (i.e. staking and shelterbelts) of apple trees, availability of
537 sufficient labour, and identification of markets, particularly given that this agroforestry system
538 is typically implemented by arable farmers without prior experience of apple production. In
539 addition, further research is needed to identify which apple varieties are best suited to
540 agroforestry conditions (Smith et al., 2016).

541 The expected time taken for cumulative GMI (expressed as NPV) of the agroforestry system
542 to exceed arable was 7 to 14 years in the theoretical systems (for the 15 of 18 cases where
543 the GMI of the agroforestry system exceeded that of the equivalent arable system), depending
544 on organic management and productivity level. This increased to 18 years in the case study
545 system, because of relatively low apple yields and high arable yields. Nevertheless, this still
546 compares favourably to timber agroforestry systems, where a return on investment is not
547 expected until at least 20 years (Graves et al., 2007; Van Vooren et al., 2016), and is
548 dependent on timber prices, grant payments and discount rates (Giannitsopoulos et al., 2020;
549 e.g. Palma et al., 2007b; Toor et al., 2012).

550 The adoption of agroforestry systems is mainly constrained by management and labour
551 complexity factors (García de Jalón et al., 2018). Although our results suggest that
552 agroforestry can increase GMI relative to arable systems, in order to effectively promote

553 agroforestry systems, farmers need to perceive that the benefits such as long-term GMI
554 exceed the perceived drawbacks. A wider valuation of non-marketable ecosystem services
555 could therefore help to promote these systems.

556 4.5 *Other ecosystem services*

557 Previous studies have demonstrated the potential for agroforestry systems to provide other
558 ecosystem services. For example, the value of reduced soil erosion by water, and balances
559 of nitrogen and phosphorous have been estimated at 5, 8 and 18 €/ha/yr respectively in a UK
560 silvoarable system compared with an arable control (Giannitsopoulos et al., 2020). In that case
561 study, the arable crop alleys were put to grass fallow after 14 years of the 30-year system
562 lifespan, therefore the value of these services in our study system is likely to be less, assuming
563 continuous arable cropping. Another important ecosystem service in some regions is soil
564 protection from wind, which to our knowledge has not yet been assessed in agroforestry
565 systems, and would be strongly spatially dependent. A holistic monetary quantification of the
566 ecosystem services provided by agroforestry, for example extended accounting systems such
567 as the Agroforestry Accounting System, would help to inform the design of public policies to
568 promote the adoption of these systems (Campos et al., 2020; Giannitsopoulos et al., 2020).

569 4.6 *Constraints and research needs*

570 Our results are based on arable and apple yield data collected over two years from five
571 agroforestry sites, the most established being 11 years. As such they would benefit from
572 further, long-term replicated studies and validation from other sites and from more established
573 systems. Long-term yield data is important to investigate biodiversity benefits, yield stability
574 and implications for food security. In addition, our assessment of pest and weed impacts on
575 crop yields are based on associations, rather than demonstrating causal relationships. Further
576 research is needed to quantify the impacts of changes in pest abundance on chemical control
577 costs (Johnson et al., 2020). Our comparison of apple pollination is constrained by

578 confounding factors, particularly organic management, tree age and landscape context, and
579 would benefit from further investigation to disentangle these factors.

580 Land equivalent ratios (LERs) are a common method for comparing productivity between
581 agroforestry systems and equivalent monocultures. LER calculates the area of monoculture
582 required to achieve the same level of productivity of one unit of polyculture, and was originally
583 devised for intercropped annual crops (Mead and Willey, 1980). We did not calculate LER in
584 this study because: (i) we did not have empirical or robust modelled yield data for the lifespan
585 of the system, particularly for apples, (ii) we did not have comparable monoculture apple
586 (orchard) yield data, (iii) as discussed by Newman et al. (2018), the method for LER
587 calculations in previous studies of agroforestry systems is inconsistent, because studies
588 variously use yield per area of the crop component or per area of agroforestry. This leads to
589 problems in comparing LER calculations from previous studies. A synthesis of previous LER
590 agroforestry studies using a standardised methodology would help overcome this problem,
591 and the data we present in this study could potentially be used in any such future synthesis,
592 notwithstanding the above constraints.

593 *4.7 Conclusion and implications*

594 There appear to be trade-offs from higher biodiversity in agroforestry systems; weed cover
595 was negatively associated with arable yields, but Bramley apple seed set, which indicates
596 pollination level, was higher in agroforestry than conventional orchard systems. Organic
597 management was a complicating factor however, and requires further investigation. In
598 addition, further research is needed to investigate yield stability in agroforestry systems arising
599 from the higher functional diversity of natural enemies.

600 Apple yield and price were the major determinants of gross mixed income (GMI) of the
601 agroforestry system, and were capable of compensating for an 11% wheat/barley yield
602 reduction in the long-term. However, the time-lag for the GMI of the agroforestry system to
603 exceed that of the equivalent arable system was substantial (at least 7 years), while labour

604 and expertise requirements represent additional barriers. Hence, policy support in the form of
605 establishment grants would help to promote these systems. This could be partially met by up-
606 front payments for carbon sequestration.

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614 anonymous reviewers for their detailed comments on the manuscript.

615 **6 Supplementary Material**

616 Supplementary Material 1. Descriptions and photographs of field sites.

617 Supplementary Material 2. Methods for predicting apple weight and pollination valuation.

618 Supplementary Material 3. Detailed model outputs.

619 Supplementary Material 4. Attributes of the theoretical modelled agroforestry system.

620 Supplementary Material 5. Results converted to pounds sterling.

621 Supplementary Material 6. Data sources.

622 Supplementary Material 7. Case study further information.

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