Agroecological farming promotes yield and biodiversity but may require subsidy to be profitable.

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Abstract

1. Intensive arable agriculture uses agrochemicals to replace ecosystem services (e.g. pest control and soil health) while simultaneously degrading others (e.g. pollination). Agroecological farming aims to reduce this reliance. Whether these practices maintain yields at a scale relevant to farm business viability is unclear.
2. In a 4-year replicated study across 17 English farms we assessed the ability of farmer co-designed agroecological systems to support regulating services, beneficial invertebrates, crop yield, and profitability. We test three management systems: 1) 'Business-as-usual (BAU)' control; 2) 'Enhancing-ES' supporting beneficial invertebrates with wildflower field margins and protecting soils with cover crops; 3) 'Maximising ES' with the further addition of soil organic matter and in-field strips to bring beneficial invertebrates into the crop.
3. Soil carbon stocks were highest in the Maximising-ES system. Predation and pollination ecosystem services were higher in the Enhancing-ES and Maximising-ES systems, as were earthworms and other populations of beneficial predatory and pollinating invertebrates. Pest snail biomass was also lowest in the Enhancing-ES and maximising-ES systems, although aphid numbers were higher.
4. The Enhancing-ES and Maximising-ES systems increases yields of cereals and oilseed rape. However, the loss of productive agricultural land and establishment costs exceeded the value of increased yields. Only Enhancing-ES breaks even only with agri-environmental subsidies.
5. These results highlight that while evidence for the role of ecosystem services in supporting crop yield can be found, overcoming economic constraints within conventional farming systems is likely to be a key barrier to widespread uptake. Agri-environmental subsidy payments can offset these costs, but only for moderate interventions. Transition to more sustainable farming systems need to overcome these economic constraints with new policy interventions.

Keywords: Agroecological; Arable; Biodiversity; Ecosystem services; Farming; Profit; Sustainable intensification; Yield.

6. Introduction

The intensification of global agriculture has devolved reliance on natural ecosystem services to agrochemicals and crop breeding, while simultaneously losing semi-natural habitats (Stoate *et al.* 2009; Pywell *et al.* 2015; Priyadarshana *et al.* 2024). In the short term this has increased yields at a level inconceivable in previous centuries but has come with negative externalities like biodiversity loss, nutrient losses and pollution burdens (Stoate *et al.* 2009; Tscharntke *et al.* 2012; Woodcock *et al.* 2016b; Defra 2023). Further, the reliance on agrochemicals may have resulted in 'intensification traps' whereby declines in biodiversity and linked ecosystem services drive ever greater dependence on high input intensive agriculture (Burian *et al.* 2024). This may over the long term threaten food production through evolution of pesticide resistance (Hawkins *et al.* 2019) and reduced resilience to climate change (Kane *et al.* 2021). Increased public awareness of the unsustainable nature of these systems has prompted both ground up interest (e.g., organic and regenerative farming movements) and top-down policy approaches to elicit system change, e.g. the EU Farm-to Fork strategy or the UK Sustainable Farming Incentives (Cusworth, Garnett & Lorimer 2021; Jaworski *et al.* 2024).

Longer-term agricultural sustainability has become increasingly mainstream (Pywell *et al.* 2015; Wezel *et al.* 2020; Heller *et al.* 2024). Such agroecological systems enhance regulating and supporting ecosystem services by increasing soil organic matter (Heller *et al.* 2024), reducing periods of bare soil (e.g. with post harvest temproary cover crops; Hufnagel, Reckling & Ewert 2020; Heller *et al.* 2024) as well as creating semi-natural habitat to increase natural pest control and pollination (Batary *et al.* 2015; Pywell *et al.* 2015; Priyadarshana *et al.* 2024). These approaches can be supported by agri-environmental scheme payments dictated by policy, as well as through industry, natural capital markets, or farmer led initiatives (Batary *et al.* 2015; Pywell *et al.* 2015; Hufnagel, Reckling & Ewert 2020).

Considerable research effort has attempted to quantify the benefits of agroecological farming practices in supporting biodiversity, beneficial invertebrates and soil functions (Tscharntke *et al.* 2012; Batary *et al.* 2015; Pywell *et al.* 2015; de Graaff *et al.* 2019; Heller *et al.* 2024). Some studies have identified benefits for regulating ecosystem services (e.g. pest control and pollination) and yield (Pywell *et al.* 2015; Woodcock *et al.* 2016a; de Graaff *et al.* 2019). However, the extent to which yield gains offset economic losses associated with establishment costs and land lost from productive agriculture (e.g. wildflower field margins don't directly produce crops) is rarely considered (Pywell *et al.* 2015). The dynamic characteristics of both economic and biological systems make such assessments complex, particularly when the contribution of regulating and supporting ecosystem services have high variability. Understanding these impacts over multi-year timescales is necessary to quantify how the cost of interventions and their associated benefits alter through time. Such research needs to be undertaken across the real-world heterogeneity of commercial farms to understand how viable agroecological farming practices are in practice (Pywell *et al.* 2015; DeLonge, Miles & Carlisle 2016). This evidence is crucial for farmer decisions to adopt sustainable agroecological systems (Goulet, Aulagnier & Fouilleux 2023).

Here we address these issues through a multi-site experiment across a 4 year rotation of 17 English arable farms. Superimposed over normal management practices for each farm were three field scale management systems: i) 'Business as usual' (BAU) considered as a conventional management control; ii) 'Enhancement of ecosystem services' (Enhanced-ES), a simple agroecological farming system incorporating wildflower strips at field margins to promote populations of beneficial insects and cover crops to reduce soil erosion over the winter; iii) 'Maximization of ecosystem services' (Maximise-ES), which adds to the Enhancing-ES management system in-field flower strips to reduce field sizes and promote spill-over of beneficial insects in to the crop with addition of organic matter to soils. These systems were co-developed with farmers to be compatible with conventional arable farms. We considered the impacts of these systems on beneficial invertebrates, regulating ecosystem services (pollination and pest control), supporting services (soil carbon), and ultimately yield and profitability. We tested the hypotheses: H1) Agroecological management practices enhance beneficial invertebrates and associated regulating ecosystem services; H2) Improving these regulating services led to increased crop yields; H3) Increases in yield are sufficiently high to offset land lost from production and management costs leading to a net benefit for farm profitability.

2. Materials and Methods

2.1 Experimental design

The experiment was undertaken over four years and replicated across 17 farms in England. Crops and their rotations varied between farms, but typically included winter wheat, other cereals (spring and winter oats and barley), oilseed rape and a break crop (e.g. beans; Table S3). All farms were managed using agrochemicals.

We identified agroecological farming practices in collaboration with our cohort of farmers that would be suitable for integration into their farming systems. These were**: 1) created non-crop semi-natural habitat**: These provide foraging resources, refuges and overwintering habitat for beneficial invertebrates including pollinators, predators and parasitic invertebrates (Pywell *et al.* 2015). We created two types of non-crop habitat interventions that could be integrated into our management systems. The first was 6m wide wildflower strips sown on field edges, which have been widely demonstrated to support populations of beneficial invertebrates (Batary *et al.* 2015; Pywell *et al.* 2015; Woodcock *et al.* 2016a). The second was 6m wide in-field strips established every 96m (three spray boom widths) running the length of the field to break up the cropped area. These in-field strips were intended to promote movement and spill-over of beneficial invertebrates into the crop (Defra 2023). Both were established by sowing 22 species of flowering forbs and grasses (Table S1). 2) **Cover crops:** When Spring sown crops (e.g. spring barley) are sown cover crops provide vegetative ground cover over the winter period protecting soils that would otherwise leave bare and so prone to erosion. They also improve drainage and act as green manure. Cover crops were established using low-cost agricultural varieties of black oats, radish, and some flowering plants (Table S2). 3) **Organic matter,** Farmyard manure from cattle, but also in some cases as green composted waste, applied in the winter prior to the first experimental harvest year. This would provide direct soil fertilisation, reduce compaction, and support beneficial soil fauna (Pulleman *et al.* 2005).

Building again on farmer led co-design the three classes of management practices were combined into management systems along a hypothesised gradient of agroecological enhancement (Fig. 1). Each management system was applied to a randomly selected field on that farm (three fields per farm, one corresponding to each of the management systems). Mean field sizes were 11.1 ha (SE±0.53, range 5.33-22.1 ha). Within a farm and for a given year the three fields were part of the same rotation, i.e. growing the same crop. These were established at 15 of the farms in autumn 2017 (monitored over 4 harvest years from 2018 to 2021), with the remaining two farms established in autumn 2018 (monitored from 2019-2021; Table S3). The three management systems were: **Business as usual (BAU) control:** here the conventional crop specific management practices typical to a given farm were in operation. Soil fertility and pest control depended primarily on inorganic fertilisers and pesticides; **Enhancement of ecosystem services (Enhancing-ES):** normal crop management practices continued, however, wildflower field margins were along ≥ 50% of the perimeter of the field (Table S4). Cover crops were sown preceding spring crops; **Maximization of ecosystem services (Maximising-ES):** In addition to practices used in the Enhancing-ES system between 1 and 3 in-field strips were established depending on the size of the field (Table S4). In addition, 30 tonnes ha^{-1} of organic matter was added in the winter before the first sampling year. Farmers participating in this study applied pesticides consistently across all three treatments.

2.2. Quantifying crop regulating ecosystem services

We focused all assessments on wheat, barley, oats (spring or winter sown crops) and winter oilseed rape. These represent the largest and most economically important crops in the UK. Sampling was undertaken along four transects in each field at 12, 24, 48 and 96m intervals from the crop boundary (16 in-crop sampling points per field; Fig. 1). The following assessments were undertaken at each sampling point (Supplementary Methods for full detail). ***Slug predation***: Slug predation by ground beetles was assessed using six artificial slugs (3 small at 15 x 3mm, and 3 large at 5 x 30mm) made from non-toxic plasticine placed out in May and June. Visual predators, like ground beetles, will attack these fake slugs (Howe, Lövei Gabor & Nachman 2009). The average number of artificial slugs with bites at sampling point was quantified. ***Aphid predation:*** At each sampling point a 2 × 10 cm piece of card with five live *Sitobion avenae* aphids glued to it was attached to a wheat tiller. These were left in place for 24 hours and the average number of aphids eaten was assessed at the field scale (Winqvist *et al.* 2011). These assessments were undertaken in May and June on winter sown cereals only. ***Aphid parasitism:*** Ten cereal stems or 10 racemes of oilseed rape were hand searched in April and June for parasitized aphid mummies. The total mean abundance per sampling point was determined. ***Pollination services:*** For oilseed rape two plants of similar size were identified at each sampling point during the pre-flowering phase in March. Insect pollinators were excluded from one plant with a fine mesh net bag. The other plant was the control exposed to insect pollinators. Pollination attributable to pollinators was determined as the average yield of the control plant minus that of the bagged plant in a field. **Soil carbon stocks**: Soil organic carbon stocks (g. cm^3) were estimated as bulk density × percentage soil carbon determined from in field soil cores and accounting for inorganic carbonates. This was assessed once at the end of the study after the final harvest (winter 2021).

2.3. *Quantifying beneficial invertebrates supporting regulating services.*

The average sampling point abundance of beneficial invertebrates for each field was annually assessed (Supplementary Methods). ***Parasitic wasps in the crop***: A vortis suctions sampler was used to collect parasitic wasps associated with (i) wheat crop pests; and (ii) oilseed rape pests in April and June each year. ***Ground active predators***: Abundance (activity density) of ground beetles, rove beetles and spiders was assessed using pitfall traps at each sampling point in April and June (20 days annual sampling). ***Canopy active predators***: In April and June inspection of cereal tillers or oilseed racemes was used to count the summed abundance of predatory invertebrates, principally aphidophagous hoverflies, lacewings, ladybirds and spiders. ***Crop earthworm counts*****:** Eight 20 x 20 x 20 cm soil monolith were extracted in October and hand sorted counting deep burrowing anecic earthworms. ***Pollinator communities in field margin areas***: In June and July 10 x 2 m off-crop transects running along the field edge were used to sampling bees, hoverflies and parasitic wasps following restrictions for weather given by Pollard and Yates (1993) (Fig. 1).

2.4. Quantifying occurrence of crop pest species

Aphids: All aphids were counted during inspection of cereal tillers and oilseed racemes when quantifying canopy active predators. ***Snails and slugs***: Wheat mash baited saucer traps were used in May of each year to sample slugs and snails. Average biomass for each group was derived. ***Arable Weeds:*** A 0.5 × 0.5 m quadrat was placed at each in-crop sampling point in June and counts of all economically important arable weed plants. We also counted tillers of Black grass (*Alopecurus myosuroides*) as a major pest in wheat.

2.5. Measuring crop yield

Yield was directly measured in each field for cereals and oilseed rape at each of the 16 within field sampling locations by hand harvesting the crop from 0.5 × 0.5 m quadrats. These were hand processed to remove chaff before calculating mean yield (tonnes ha^{-1}). We used precision yield from GPS linked combine harvesters to validate these estimates. This was available from 36 field and year combinations, (*c.* 24% of the fields monitored across years) and showed a strong correlation with in-field quadrat measurements (Fig. S1. *Precision yield = 0.93 + 0.77 × quadrat yield*, $F_{1,34}$=46.7, p<0.001, R^2=0.58). As the quadrat-based approach underestimated yield relative to the precision agriculture yields this equation was used as a correction factor. This was done to avoid systematic under-estimation of field productivity.

2.6. Economics of agroecological farming systems

The following summarises the economic assessment, with full detail provided in the Supplementary Methods and Table S5. To assess the annual balance of profit and loss for each farming system (cereal and oilseed rape), a base line predicted profit per field (GBP £ per field) was determined from the measured yield and crop prices (4 year mean of published commodity prices 2018-2021). We deducted the costs associated with of loss of productive land (e.g. the value of foregone crop production), and consumable and management costs for the Enhancing-ES and Maximising-ES systems for each field and year. For the UK governmental agri-environmental scheme (AES) payments are available for field margins, infield strips and cover crops established in the Enhancing-ES and Maximizing-ES systems (Defra 2023). We therefore also derived profit (GBP £ ha^{-1}) accounting for these subsidies (Table S5).

2.7. Analysis

We assessed the response of yield (crop tonnes ha^{-1}) and profit (GBP £ ha-1) with and without AES government subsidies to the management system (BAU, Enhancing-ES, Maximising-ES), year since establishment, crop type (spring and winter sown wheat, barley and oats as well as oilseed rape) and all interactions using general linear mixed models within lme4 in the R Statistical Environment (Bates *et al.* 2010; R_Core_Development_Team 2023). Random effects for the intercepts were specified as year since establishment nested within farm. Using the same generalised linear mixed model structure, regulating service provision (i.e. slug predation, aphid predation and oilseed rape pollination; soil carbon), beneficial invertebrate mean abundance (i.e. earthworms, ground beetles, rove beetles, spiders, hoverflies, bees and parasitoids) and crop pests (e.g. slug and snail biomass or weed counts) were assessed in response to management system, year and their interaction. The response metrics were all continuous (e.g. average plot abundance) and so modelled initially using a Gaussian distribution with identify link. Assessment of these initial models was undertaken using the DHARMa package (Hartig 2022). In most cases deviations identified by this process were addressed using a $\log_e$ (N+1) transformation of the response. For continuous but overdispersed data a Tweedie distribution with log link was used within glmmTMB (Brooks *et al.* 2017). Models were simplified using deletion of least significant effects using either likelihood ratio tests F-test (normally distributed) or χ^2 (Tweedie distributed). Data were excluded for three occasions where the crops in a field for a particular year failed to establish. Some analyses were restricted to crops where that data was collected (i.e., pollination and oilseed pest parasitoid abundance to oilseed rape, cereal parasitoid abundance to cereal crops, and aphid predation to winter wheat).

3. Results

Across the 17 sites and 4 years 246,232 surface active predators were collected from the crop (115,191 ground beetles, 35,299 rove beetles and 95,742 spiders), 30,435 parasitic wasps and 11,791 aphids of which 16.7% (1,974) were parasitized. Within the field margins 2,431 bees and 4,477 hoverflies were recorded. Overall, 67.6% of crops were cereals (43.1% spring and 56.9 % winter sown) with winter wheat being the most frequent of these (39.2%).

3.1. Supporting and regulating ecosystem services

Supporting and regulating ecosystem services benefited from the establishment of agroecological farming systems. Soil carbon stocks were found to differ between the three management systems ($F_{2, 33.2}$=13.8, p<0.001; Fig. 2a), being significantly higher within the Maximising-ES treatment than the BAU control (t_{30}=3.14, p<0.001). Aphid predation was significantly higher in the Enhancing-ES and Maximising-ES treatments ($F_{2,51.4}$ =9.79, p<0.01, Fig. 2b). Neither slug predation rates ($F_{2,93.3}$=1.99, p>0.05; Fig.2c) nor counts of mummified aphids (χ^2_1=4.99, p<0.1; Fig. 2d) differed significantly between the management systems. However, in both cases there was a non-significant trend for these to be higher in the Maximising-ES treatment. Seed set of oilseed rape attributable to insect pollination differed between the management systems ($F_{2,9}$ =6.19, p=0.02; Fig. 2e) with the Enhancing-ES system being marginally higher than BAU (t_9=2.13, p=0.06) and significantly higher for the maximising-ES treatment (t_9=3.49, p<0.01). Overall effects of years since establishment were identified for aphid parasitism (χ^2_1=24.9, p<0.001) and aphid predation ($F_{3,23.7}$ =5.11, p<0.01). This was not a continuing temporal trend but varied in magnitude between years. No year and management system interactions were found (p<0.05).

3.2. Populations of beneficial invertebrates

The provisions of within crop ecosystem services are underpinned by components of native biodiversity present within the crops and immediate surrounding habitat. There was evidence that the agroecological management systems increased population sizes for anecic earthworms

(Treatment × year: $F_{6,97.6}$ =2.49, p=0.03; Fig 1f), spiders ($F_{2,96.5}$ =7.36, p<0.01; Fig 1n), crop-canopy predators (χ^2_2=8.03, p=0.02; Fig. 2k), bees (Treatment × year: χ^2_6=14.2, p=0.03; Fig 2m) and hoverflies (Treatment × year: χ^2_6=13.7, p=0.03; Fig. 2n). For these the Maximizing-ES systems supported higher populations than the BAU control, with the Enhancing-ES system supporting greater populations than the control only for earthworms, spiders, bees, and hoverflies. For the earthworms and hoverflies, the significant year and management system interaction showed that the first year of monitoring had lower population sizes. Management system had no significant effect on within crop abundance of ground beetles ($F_{2,95.1}$=0.54, p>0.05; Fig2h), rove beetles ($F_{2,96.9}$=1.90, p>0.05; Fig. 2j), cereal pest parasitoids ($F_{2,78.2}$=1.62, p>0.05), oilseed rape parasitoids ($F_{2,18}$=0.08, p>0.05; Fig. 1g), or the off crop field margin parasitoid density ($F_{2,100.2}$=0.18, p>0.05; Fig 2o). There was an unexpected significant negative effect of management treatment of margin-active parasitoids (χ^2_2=0.04, p=0.04; Tweedie distribution; Fig 2o) indicating abundances were lower in general in the maximising-ES treatment than the BAU (z=2.58, p<0.01). Significant year effects were seen for earthworms ($F_{3,37.0}$ =6.80, P<0.001), crop-canopy predators (χ^2_3 =8.91, p=0.03), oilseed pest parasitoids ($F_{3, 9.0}$=6.80, p=0.01) and cereal pest parasitoids ($F_{3, 28.1}$=2.96, p=0.04). No other significant effects were found (p>0.05).

3.3. Pest populations within the crop

Creating farming systems that may benefit beneficial invertebrates runs the risks of also promoting pest populations. Aphid numbers responded to management system (χ^2_2=6.00, p=0.05; Fig. 2s) with the Maximising-ES treatment having slightly higher numbers than the BAU control (z=2.14, p=0.03). Snail biomass was affected by an interaction between management system and year (χ^2_6=15.7, p=0.02; Tweedie distributed; Fig. 2q), although the overall trend was for lower biomass in the enhancing-ES (z=-3.10, p=0.02) and maximising-ES treatments (z=-3.16, p<0.001) relative to the control. Management system had no effect on slug biomass (χ^2_2=1.07, p>0.05; Fig. 2p) and arable weed abundance (χ^2_2=0.23, p>0.05; Fig. 1s). While Black Grass tiller abundance was not significantly affected by management system, there was a trend of it being lower in the Enhancing-ES and Maximising -ES systems (χ^2_2=0.89, p>0.05; Fig. 2r). Aphids (χ^2_3=19.9, p<0.001), slug biomass (χ^2_3=17.7, p<0.001) and arable weeds (χ^2_3=19.4, p<0.001) showed inter annual variation. No other significant effects were identified (p>0.05).

3.4. Yield and Profitability

Yield represents how effective our agroecological management systems have been in promoting key ecosystem services. Crop yield differed between the management systems ($F_{2,97.6}$=6.01, p<0.01), with higher yields within the cropped seen for both the Enhancing-ES (t_{97}=2.87, p<0.01) and Maximising-ES (t_{97}=3.14, p<0.01)) management systems relative to BAU control (Fig 3a). Yield was also affected by crop type ($F_{6,47.1}$=29.5, p<0.001) but not an interaction between crop and management system (p>0.05). Model estimates suggested that relative to the BAU control the enhancing-ES treatment increased yields by 0.30 (SE ±0.11) tonnes ha^{-1} across all crops and by 0.32 (SE ±0.10) tonnes ha^{-1} for the maximising-ES system. Yield was significantly affected by year, although there was no clear temporal trend with the second and fourth years being higher yielding ($F_{3,38.7}$=6.36, p<0.01).

Agroecological management comes at a cost in terms of the management to establish it as well as crop yields forgone to land converted to field margins and in-field strips (Table S4). Profit affects farmer attitudes to viability and adoption for agroecological farming systems. Profit was significantly affected by management system ($F_{2,95.0}$=64.7, p<0.001), year since establishment ($F_{3, 32.1}$=2.92, p<0.05) and crop type ($F_{6, 40.2}$ =2.92, p<0.05). There was no interaction between crop and management system (p>0.05). The cost of establishing the agroecological farming systems relative to BAU meant that profit was significantly lower in the Enhancing-ES (t_{95}=-3.86, p<0.001) and Maximising-ES treatment (t_{95}=-11.1, p<0.001) (Fig3b). Model estimates suggested that the Enhancing-ES system and maximising-ES systems were respectively on average 83.9 (SE ±21.7) and

240.6 (SE ±21.7) GBP £ ha^{-1} $year^{-1}$ less profitable the BAU control. This reduced profitability is in part due to establishing field margins, in-field strips and cover crops (Fig S3). When AES subsidies are present, net profit is still significantly affected by management system ($F_{2,94.9}$=29.0, p<0.001), crop type ($F_{6, 39.9}$ =11.33, p<0.001) and year ($F_{3, 32.0}$ =2.95, p<0.05). However, the inclusion of AES subsidies meant that while the enhancing-ES system was no longer significantly different from BAU, the Maximising-ES treatment remained significantly less profitable (t_{95}=-6.95, p<0.001) by on average 144.1 (SE ±20.8) GBP £ ha^{-1} $year^{-1}$ (Fig. 3c).

4. Discussion

We have directly tested the efficacy of integrating agroecological measures into intensive arable agriculture both from the perspective of effects on proximate drivers, like regulating ecosystem services and beneficial invertebrates, as well as on end points of yield and profitability. Ultimately farms are businesses, and farmer decisions for adoption will always include consideration of economic viability (Sakrabani *et al.* 2023). Fostering agroecological farming requires evidence not just its environmental effectiveness but also its farm economic implications. This is critical for identifying economic drivers to elicit system change to promote greater sustainability, including government agri-environmental payments, commodity premiums for sustainable systems and natural capital markets.

4.1. Regulating ecosystem services and beneficial invertebrates.

Reintroducing key resources at local and landscape scales, often through creation of semi-natural habitats, like wildflower field margins, is a key approach to promote populations of beneficial insects (Batary *et al.* 2015; Pywell *et al.* 2015; Priyadarshana *et al.* 2024). Approaches like in-field strips are an extension of this concept that facilitates spill-over of beneficial invertebrates from off-crop areas into the crop (Woodcock *et al.* 2016a; Defra 2023; Priyadarshana *et al.* 2024). These interventions underlie our Enhancing-ES (field margins and cover crops) and Maximising-ES (field margins, in-field strips, cover crops and organic matter) management systems. These were intended to provide critical foraging, breeding and overwintering resources for beneficial invertebrates though which we show here positive effects on spiders, earthworms, sward active predatory invertebrates, as well as off-crop bees and hoverflies. Increases the population of these beneficial invertebrates had knock on benefits for some regulatory ecosystem services.

Predation rates of aphids were highest within the enhancing-ES and maximising-ES management systems. This corresponds with increased abundances of crop active predators, like ladybirds, hoverfly larvae, and spiders. There was also a trend, albeit non-significant, of increasing rates of aphid parasitism by Hymenoptera under the maximising-ES management system. Unlike aphid predation, rates of slug predation showed no response to the agroecological farming systems, a finding which was concordant with the absence under these management systems of populations changes in ground or rove beetles. Why the creation of field margins and in-field strips had no apparent benefit on abundance of crop ground and rove beetle populations is unclear. A meta analytical review suggested that these taxa may be less sensitive to increased availability of semi-natural habitat than other invertebrate natural enemies (Shackelford *et al.* 2013). However, by grouping these taxa together and ignoring individual species responses we may not be quantifying community level responses between the management systems (Jowett *et al.* 2019). It is likely that a focus on this metric may conceal specific responses for species with high pest attack or consumption rates (Greenop *et al.* 2020). This may explain why the biomass of snails under the Enhancing-ES and maximising-ES treatments was lower than the BAU treatment, with this being driven by populations of specific species, e.g. large *Pterostichus* spp.. While pollination was assessed only for oilseed rape, we found strong evidence that seed set was highest in the maximising-ES management systems. This is consistent with the increased densities of bees and hoverflies within the sown field margin areas of this management system.

4.2. Crop yield benefits from agroecological farming systems.

While crop yield is only one aspect of agricultural production, with aspects of quality (e.g. oil or protein content) and aesthetics (e.g. blemishes on fruits) being important, it remains of major concern to farmers. When we focussed on the economically most important crops of cereals (wheat, barley and oats) and oilseed rape, we found that yield responded positively to both agroecological farming systems. Model predictions suggested an increase of *c.* 0.3 tonnes ha^{-1} across all crops for the Enhancing-ES and Maximising-ES, although average individual yields of crops differed. Outside of increases in beneficial invertebrates and the ecosystem services they provide, the addition of organic matter (principally farmyard manure) applied in the initial year of the Maximising-ES management is also likely to have increased yields relative to the Enhancing-ES system. However, while farm yard manure provides nitrogen, phosphorus and potassium, it has a low bioavailability with 10% of these nutrients available for the first crop and 5% for the following (AHDB 2023). Certainly, a recent meta-analysis suggests that organic amendments may have largely substitutive (as opposed to additive) effects on yield when analysed with synthetic fertilisers (MacLaren *et al.* 2022). Applied only before the first year of the study its contribution to the overall trends in yields may therefore have been relatively small. In the medium term, adding organic matter improves soil structure, nutrient supply, and microbial activity which may have accumulating positive yield impacts. In the longer term, it enhances soil organic matter (as found in this study) and so helps sequester carbon (Johnston, Poulton & Coleman 2009). In the Enhancing-ES where no farmyard manure was applied, as well as more generally for the Maximising-ES treatment over the 4 years of the rotation, yield differences are therefore likely to have been linked to a large part with maximising other regulating ecosystem services like pollination and pest control.

4.3. Conditions for economic viability

Profit margins are arguably more relevant than yield for farmer decisions as they integrate the hidden costs associated with different management systems.   We have shown that changes in management that enhance beneficial invertebrates and regulating ecosystem services have positive effect on yield. However, this increase comes at a cost in land forgone to production, as well as establishment and subsequent management.   Profitability of the investigated agroecological farming systems is achieved only under certain circumstances. Critically as management interventions move from trying to enhance ecosystem services (wildflower field margins and cover crops) to attempts to maximise them (wildflower field margins and in-field strips, cover crops and organic matter) the cost increases. This means that without agri-environmental scheme subsidies for wild flower field margins, in-field strips and cover crops, neither of the agroecological farming systems would have been profitable.   Even, so subsidies as they currently exist are only sufficient to make the Enhancing-ES system comparable in profit to the BAU control. Without subsidies there is a negative correlation between profit and the ratio of agri-environmental interventions (wildflower field margins and in-field strips) to cropped area (Fig. S3).   Subsidising farmers for management that has societal benefits (e.g. biodiversity) may be critical to facilitate transition to lower impact farming systems (Batary *et al.* 2015). The importance of such subsidies to ease the transition to agroecological farming therefore remains critical.

The unprofitability of the maximising-ES system, even with agri-environment subsidies, will likely act as a barrier to its adoption. This failure to be profitable is associated in part with an absence of subsidies for organic matter additions (Defra 2023). As a result, while addition of farm-yard manure increased soil carbon stocks, their use had an insufficient impact on yields to offset losses in profit.   In addition, the cost of bulk organic matter products may be high relative to any short term (e.g. 4 year) capacity for them to increase yields. This issue is exasperated by the polarisation of UK farming systems to either livestock or arable (often with a regional bias) (Stoate *et al.* 2009).   On farm composting may represent alternatives, albeit one with scaling issues, to providing organic matter sources that don't rely on livestock, while more circular local supply through municipal links (e.g. green composted waste) could also provide opportunities for low-cost organic matter sources. It is worth noting that results from the precision yield data alone (collected by certain types of combine harvesters and so available for only a limited number of sites) demonstrated that the Maximising-ES system increased average yields by double that of the Enhancing-ES system (c. 0.6 tonnes ha^{-1}) (Fig. S2). Precision yield data accounts for within-crop variability in yield (e.g. patches of high pest pressure) that may be missed by quadrats. Such an increase if typical of other fields would increase the economic viability of more intensive agroecological interventions.

5. Conclusions

Our results provide some optimism for an economic basis to promote the adoption of complex agroecological farming systems. However, as the complexity of the agroecological interventions increases they become less profitable within the current economic environment, even with subsidies. In the absence of new financial drivers for adoption individual farmer attitudes will likely remain the ultimate limitation to complex agroecological systems uptake, particularly where these require significant investment of effort or deviation from experiential comfort zones (Comer *et al.* 1999; Burian *et al.* 2024; Follett *et al.* 2024). Even so, evidence that some agroecological farming systems can meet an economic breakeven point may encourage adoption. Attitudes within the farming community acknowledge the need to future proof farming systems, particularly in the face of declining soil health, pesticide resistance, and future environmental stresses like climate change (Comer *et al.* 1999; Novickyte 2019; Jaworski *et al.* 2024). As a result, farmer attitudes may well be shifting to increased acceptance to adopt such practices even at the risk of reduced short-term profit if it infers longer term farm business sustainability benefits. Supporting farmers to better understand how effective agroecological farming practices have been on a site-by-site basis may also be a critical step breaking farmers free from 'intensification traps' (Burian *et al.* 2024). Better training in agroecological management and advances in farmer led ecosystem services monitoring may further help to address uncertainty in these systems promoting adoption (McCracken *et al.* 2015; Shirali *et al.* 2024). Overall, enhancing ecosystem services creates an opportunity to reduce agrochemical inputs, saving costs and reducing environmental impacts.

Statement of authorship: Analysis and first draft by BW, with revisions by all authors. Experimental design by BA, SC, MS, CC, MN, JS, JB and RP. Field and lab work by LH, SH, MT, JS, JR, MW, with data management from RO.

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Conflict of interest: MN provides agronomic advice to farmers to establish field margins. Otherwise no conflicts of interest.

Data accessibility statement: R code and data available through GitHub at https://github.com/BenAWoodcock/Woodcock_ASSIST_agroecological_enhancement. If published this will be made available through Zenodo with an associated DOI.

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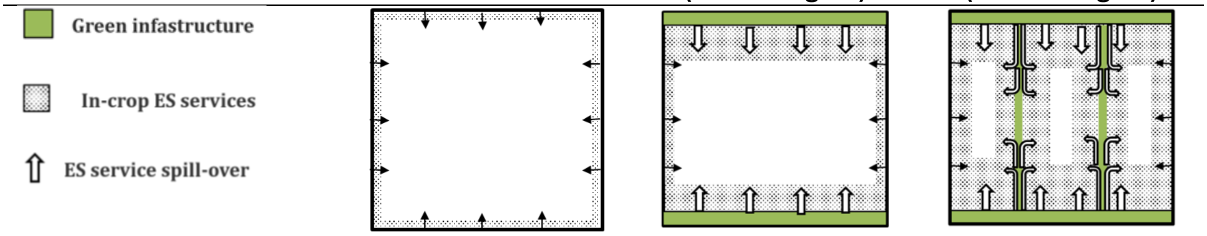
Figure legends

Fig. 1. Pictorial representation of the composite management systems applied to three fields in each of 17-replicate UK farms, including a visualisation of the sampling strategy.

Fig. 2. Boxplots showing the effect of agroecological farming systems across the 17 farms and 4 years on supporting and regulating ecosystem services, as well as pest populations. Letters indicate significant differences from the BAU control. For each boxplot the central line represents the median, with the box spanning the 25^{th}-75^{th} interquartile range.

Fig. 3. Boxplots comparing crop yield and profit for the three farm management systems over 4 years. Yield is expressed as an effect size (standard mean difference) to account for between crop type differences in average yield.

Fig. 1



	Management system treatment		
	Business as usual (BAU)	Enhancement of ecosystem services (Enhancing-ES)	Maximization of ecosystem services (Maximising-ES)
Flower rich field margins	None	6m flower rich strips along 50% of the field edge.	6m flower rich strips along 50% of the field edge.
Cover crops	None	Simple mixtures of oats, radishes and forbs sown before spring sown crops.	Simple mixtures of oats, radishes and forbs sown before spring sown crops.
In-field flower strips	None	None	6m wide in-field flower strips every 96 m.
Organic matter	None	None	Farmyard manure (30 t. ha^{-1} in year one only.

In-field sampling points and field margin transect

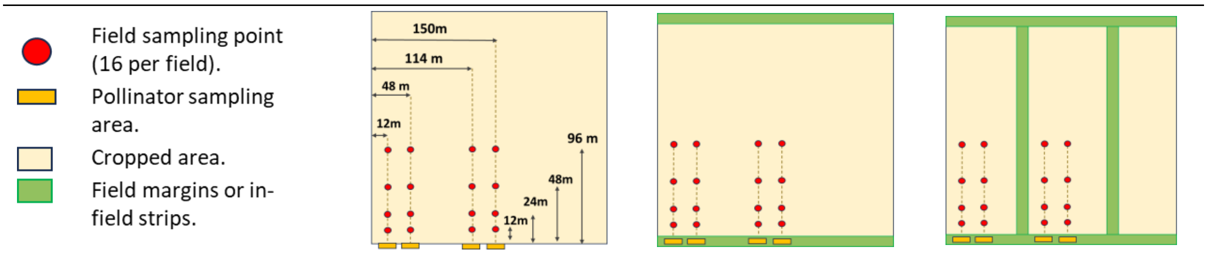
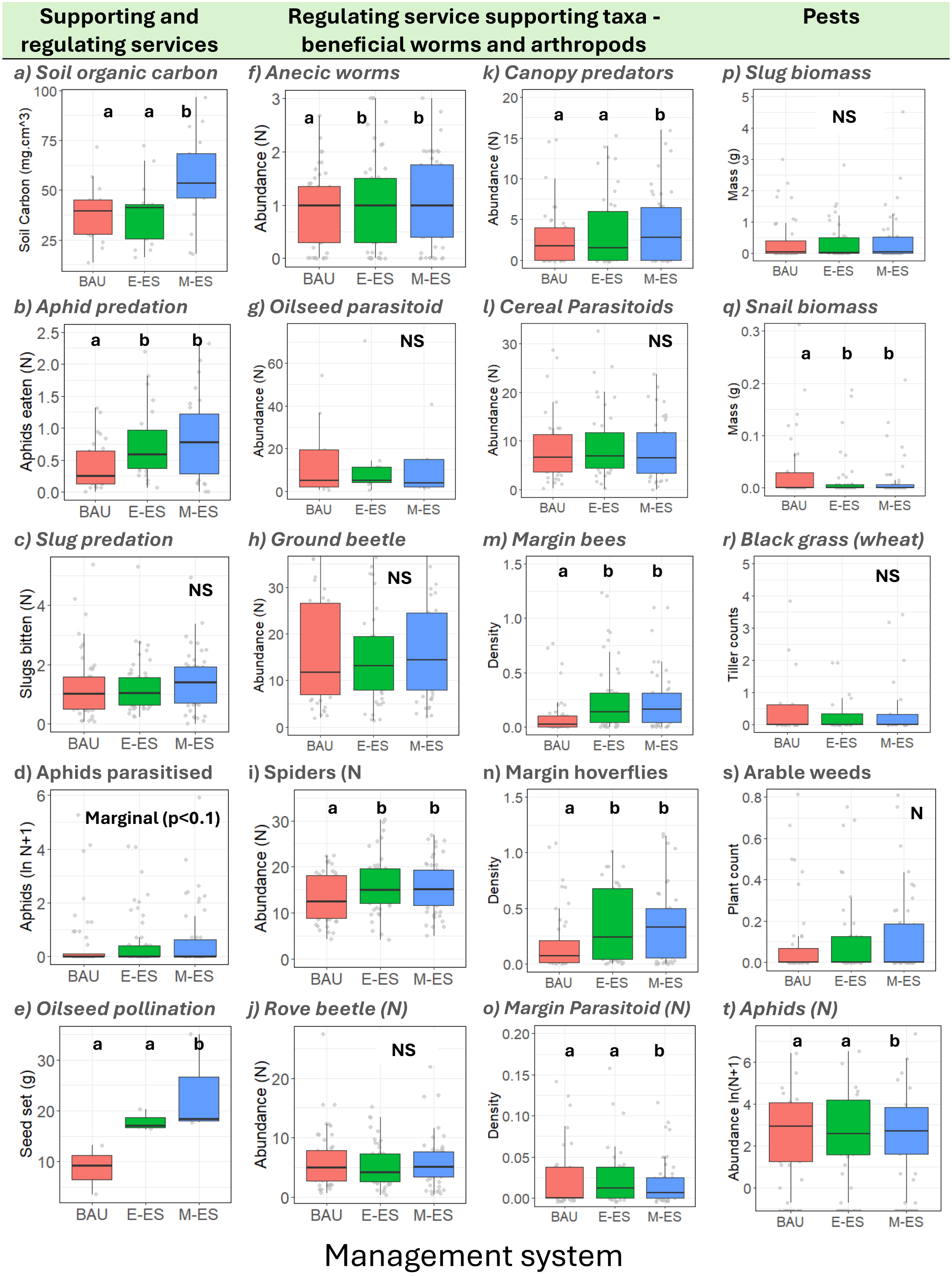
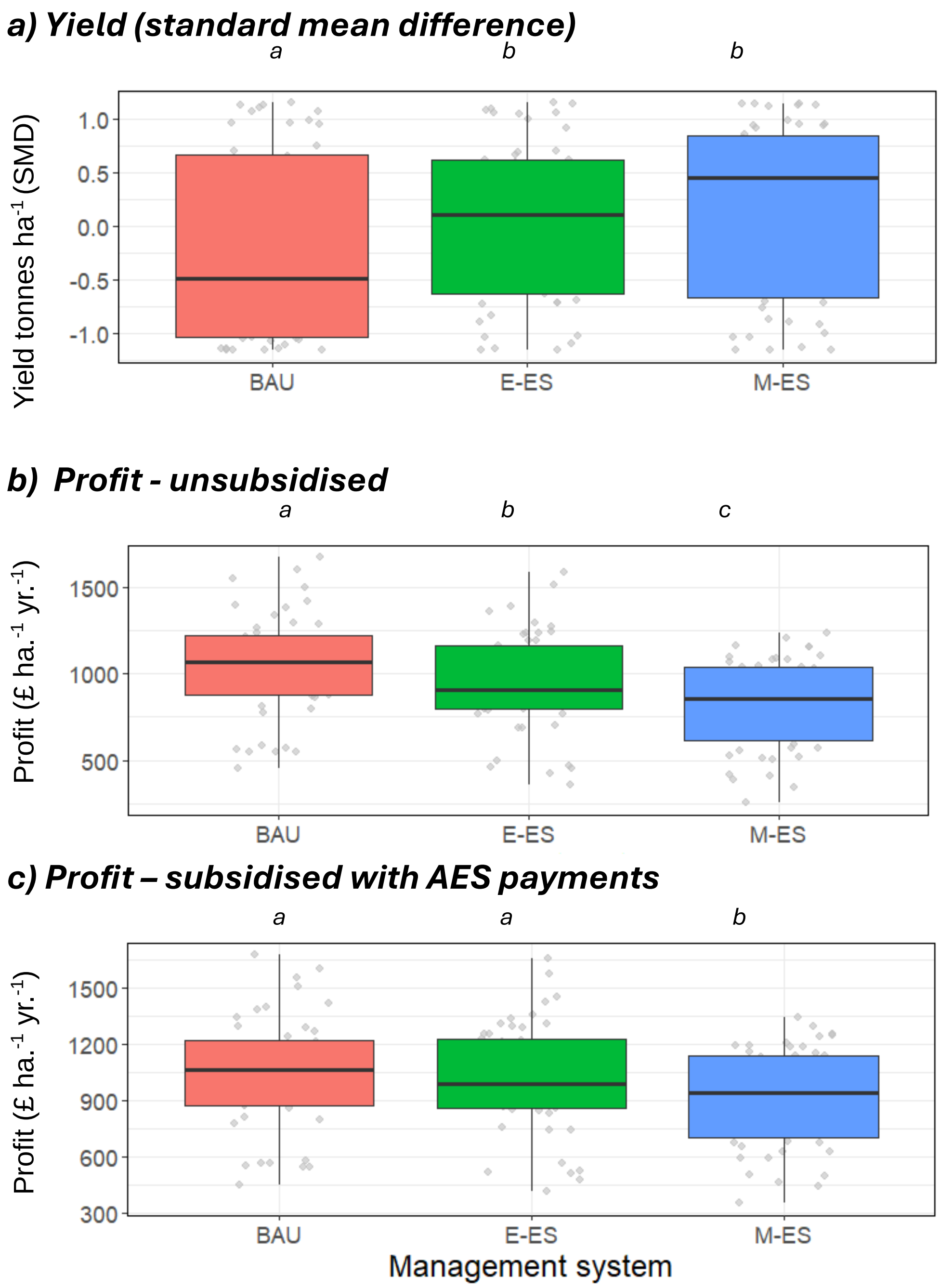


Fig 2



Supporting and regulating services
Regulating service supporting taxa - beneficial worms and arthropods
Pests
a) Soil organic carbon
Soil Carbon (mg.cm^3)
a a b
f) Anecic worms
Abundance (N)
a b b
k) Canopy predators
Abundance (N)
a a b
p) Slug biomass
Mass (g)
NS
b) Aphid predation
Aphids eaten (N)
a b b
g) Oilseed parasitoid
Abundance (N)
NS
l) Cereal Parasitoids
Abundance (N)
NS
q) Snail biomass
Mass (g)
a b b
c) Slug predation
Slugs bitten (N)
NS
h) Ground beetle
Abundance (N)
NS
m) Margin bees
Density
a b b
r) Black grass (wheat)
Tiller counts
NS
d) Aphids parasitised
Aphids (ln N+1)
Marginal (p<0.1)
i) Spiders (N
Abundance (N)
a b b
n) Margin hoverflies
Density
a b b
s) Arable weeds
Plant count
N
e) Oilseed pollination
Seed set (g)
a a b
j) Rove beetle (N)
Abundance (N)
NS
o) Margin Parasitoid (N)
Density
a a b
t) Aphids (N)
Abundance ln(N+1)
a a b
BAU
E-ES
M-ES
Management system

Fig. 3


a) Yield (standard mean difference)
a
b
b
Yield tonnes ha-1 (SMD)
1.0
0.5
0.0
-0.5
-1.0
BAU
E-ES
M-ES
b) Profit - unsubsidised
a
b
c
Profit (£ ha.-1 yr.-1)
1500
1000
500
BAU
E-ES
M-ES
c) Profit – subsidised with AES payments
a
a
b
Profit (£ ha.-1 yr.-1)
1500
1200
900
600
300
BAU
E-ES
M-ES
Management system