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Full Length Article

Economic valuation of pest regulation benefits provided by arthropods in the UK

Peter King [a,*], Theresa Robinson [b], Charlotte Howard [b], Tom D. Breeze [b], Martin Dallimer [c]

[a] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[b] Centre for Agri-Environment Research, School of Agriculture, Policy and Development, University of Reading, Reading RG6 6AR, UK
[c] Centre for Environmental Policy, Faculty of Natural Sciences, Imperial College London, London SW7 1NE, UK

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ABSTRACT

The role of arthropods as regulators of crop pests has gone underexamined in comparison to those species that are crop pollinators. While pollination services have been widely studied, the economic value of pest regulation provided by natural enemies remains underexplored. The suppression of insect crop pests by these natural enemies may provide substantial value to agriculture in reduced crop losses. Here, we estimate the economic value of pest regulation services provided by arthropod natural enemies in the UK for wheat (*Triticum* spp.), barley (*Hordeum vulgare*), and oilseed rape (*Brassica napus*) crops. We used a structured literature search to parameterise an economic production function to estimate the average annual value of pest regulation provided by arthropod natural enemies in the UK. We then simulated changes in economic benefits across different levels of natural enemy presence. A marginal 10% reduction from a full community of natural enemies had an estimated value per hectare between £108.98 – £171.13 for barley, £36.93 – £73.97 for oilseed rape, and £0.74 – £9.60 for wheat. We performed sensitivity analysis to evaluate how robust these benefits were across field management strategies. There are areas of uncertainty around the efficacy of natural enemies, crop yield response, economic thresholds, and field management. Resolving these sources of uncertainty and quantifying the economic value of pest regulation could inform sustainable pest management strategies and wider insect conservation practice.

1. Introduction

There is an increasing demand for improved agricultural productivity and crop yield due to the food requirements of the growing world population (Naranjo et al., 2015; Woodcock et al., 2016). With up to 40 % of global cereal crops lost to pests (Bruce, 2010), realised crop yields could be improved by suppressing arthropod pests through chemical or biological means (Ortega-Ramos et al., 2022). The most common pest control mechanism is the application of insecticides, which can effectively control populations of insect pests, e.g., aphids (*Sitobion avenae, Rhopalosiphum padi*). However, the efficacy of insecticide application faces multiple challenges including the development of resistance in target pests (Williams et al., 2010), adverse effects on beneficial non-target species (Coston et al., 2023; Naranjo et al., 2015), soil contamination, and the increasing cost of insecticide application (Ramsden et al., 2017). Further pressure to avoid insecticide application comes from government agencies interested in regulating and restricting the application of many insecticides (European Commission, 2013; 2019), including the farm-to-fork initiative for 50 % reduction in pesticide usage (Silva et al., 2022), and restrictions on neonicotinoids with their potential for adverse effects on non-target species including bees (Krupke et al., 2017) and parasitoid wasps (Ortega-Ramos et al., 2022; Williams et al., 2010). Together, these factors underscore the importance of biological pest control to improve crop yields.

The suppression of insect crop pests by a community of arthropods natural enemies, such as predatory insects, spiders, and parasitoids (Klinnert et al., 2024), represents a valuable ecosystem service on agricultural land (e.g., Dainese et al. 2017; Letourneau et al. 2015; Zhang et al., 2018). Although these beneficial arthropods occur naturally in crop fields and adjacent semi-natural habitats, they face threats from habitat loss, lack of available resources, and non-target effects of insecticides (Gurr et al., 2017). These threats risk undermining biocontrol services and create a need for management strategies that can reconcile crop productivity with natural-enemy conservation.

* Corresponding author.
E-mail addresses: P.King1@Leeds.ac.uk (P. King), Theresa.Robinson@jncc.gov.uk (T. Robinson), c.howard@reading.ac.uk (C. Howard), t.d.breeze@reading.ac.uk (T.D. Breeze), m.dallimer@imperial.ac.uk (M. Dallimer).

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Conservation Biological Control (CBC) is one such approach to pest management which focuses on conserving naturally occurring organisms that can provide pest control services (natural enemies). This can involve a range of strategies including the use of selective insecticides that minimise harm to natural enemies (Torres and Bueno, 2018), or habitat enhancement to better support natural enemies (Begg et al., 2017. Li et al., 2021).

Quantifying the economic value of these pest control services is crucial to the understanding of the contribution of natural enemies to pest regulation. Estimates of the value of pest control ecosystem services are often specific to the crop system and location with examples from barley (Ostman et al., 2003), and soybean (Zhang and Swinton, 2012), and wheat where, for example Zhang et al. (2018) found the annual value of pest regulation to be worth £0-2.3million for one region of UK. Despite their potential economic importance, ecological-economic research into naturally occurring natural enemies has been limited by a lack of suitable data used to build bioeconomic models that quantitatively link natural enemy populations to yields (Lundin et al., 2012; Dainese et al., 2017, Naranjo et al., 2015). The main building blocks of an economic model, price, and yield are not always spatially or temporally disaggregated, with many studies using aggregate whole-country sale prices (Zhang et al., 2018). There is a relative scarcity of evidence on economic thresholds (Ramsden et al., 2017), the effect of different control measures on pest species (Lundin et al., 2012), and relationships between plant injury and yield (Dainese et al., 2017). For the parameters that influence the yield response, Zhang and Swinton (2012) note that even in the relatively well-studied crop system of wheat, such links must be species-specific to reduce uncertainty around their estimates. Consequently, crop yield functions to explain the impacts of natural enemies often rely on expert opinion (e.g., Zhang et al., 2017).

The aim of this study is to evaluate the economic benefit of natural pest regulation services provided by natural enemies in three major arable crop-systems in the UK, a country where the area dedicated to oilseed rape has almost halved in response to insecticide regulations (Coston et al., 2023) yet annual crop production still exceeds £1 billion in value (DEFRA, 2023). We aimed to describe how this value responds to insect pest pressure, natural enemy presence, and field management strategy, and elucidate opportunities for further research to help reduce uncertainties. We designed a production function that linked changes in the presence of natural enemies and pests to crop yields across wheat (*Triticum* spp.), barley (*Hordeum vulgare*), and oilseed rape (*Brassica napus*) crops, and illustrates how changes in relevant insect pests (aphids for wheat and barley, cabbage stem flea beetle for oilseed rape) and natural enemies can have significant economic benefits. To obtain the necessary parameters for our models, we initially carried out a structured review of the existing published evidence to identify suitable data for use as inputs for a production function. Building on prior estimates (Zhang and Swinton, 2012; Zhang et al., 2018), our contribution is a national-scale, multi-crop assessment of the economic value of biocontrol that considers broader pest- natural enemy interactions and yield responses.

2. Methods

2.1. Study system

This study estimates the economic value of pest regulation provided by natural enemies in the UK at a national scale between 2011–2021, some of the latest years with validated market data. We selected the UK as a country with a valuable crop market, available market data (DEFRA, 2023; Nix, 2021), and demonstrated history of pest regulation studies (e.g., Beynon et al., 2015; Ramsden et al., 2017). We focused on three common crops in UK arable crop rotations, with a combined annual produced volume in the millions of tonnes, with an average annual worth of £4.5bn (DEFRA, 2023); wheat (*Triticum* spp.), barley (*Hordeum vulgare*), and oilseed rape (*Brassica napus*). These crops were chosen for three reasons, (a) they may feature in a typical crop rotation, (b) are among the most grown consumer crops in the UK (Zhang et al., 2018, (c) there was available data on their pests, response to natural enemies, and yield response; (Ostman et al., 2003) and (d), in the case of oilseed rape, is severely affected by pest pressures (Williams, 2010).

2.2. Overview of the production function approach

We used a production function model to estimate the current economic value of pest regulation, defined as the change in lost crop yields due to insect pests. Production functions, a method with strong links to economic theory (Farnsworth et al., 2015), have been widely applied in agricultural ecosystem valuation, including for biological pest control (De Groot et al., 2012; Daniels et al., 2017). Daniels et al. (2017) used a production function to estimate the value of pest regulation in pear crops in Flanders for 2011, while Landis et al. (2008) used a production function to estimate the value of biocontrol given pests effects on soybean crop yields. Alternative economic valuation methods, such as the economic surplus approach, (Letourneau et al., 2015; Zhang et al., 2018), require a broader range of data on ecological factors including initial pest density and population dynamics (Zhang and Swinton, 2012), and economic data, such as supply and demand elasticity (Zhang et al., 2018). However, few of these data points are available at sufficient resolution for our nationwide case study of the three crop systems in the UK from 2011:2021. We, therefore, used the more tractable production function method, which directly linked changes in the population of natural enemies to changes in the value of yield lost per hectare. The production function approach results in a simple model with an estimate of lost yield per hectare but may have large uncertainties around the estimates if the component parameter estimates are themselves uncertain. Our production function builds on previous work by including more crop systems and using available data on natural enemy effectiveness at reducing insect pest damage.

2.2.1. Parameterisation

To assess data availability for our production function on crop-specific pest-natural enemy relationships and yield impacts, we conducted a structured literature search, drawing on guidelines associated with 'rapid evidence assessments' (Collins et al., 2015). We recovered data relevant to the development of our production function i.e. crop-specific parameters on initial pest density, the effect of natural enemies on pest populations, and the effect of pest density on yields. Further discussion of the process is available in supplementary materials (Table A1, Fig. A1).

2.2.2. Specification

All variables used in the production function, their values, sources, and functions are reported in Table 1 with an illustrative flowchart in Fig. 1. We built our production function with four steps. The first step was to estimate how pest abundance responds to the presence of natural enemies. We started with an empirically supported assumed number of pests (Zhang et al., 2018) rather than attempting to recover pest abundance in traps and then validly scale those down to farm field levels (c.f., Coston et al., 2023; Lundin et al., 2020; Ramsden et al., 2017). We followed Zhang et al. (2018) in assuming different initial pest density conditions: low, medium, and high, with the density units varying by crop system; aphids/tiller (wheat, Zhang et al., 2018), aphid/days (barley, Ostman et al., 2003), flea beetles per trap day (oilseed rape, Zhang et al., 2017). To model the population of natural enemies in the absence of high-resolution field data on the population of different natural enemies given that individual species will vary across space and between pests, we instead used a single parameter in the range [0, 1] representing the change from a full community of arthropod natural enemies with all relevant predators and parasitoids (1), to a complete absence of any natural enemies (0). We, therefore, generalise the entire

Table 1
Variable name, description, source, and assumed values for all inputs to the production function. Illustrated in Fig. 1.

Variable	Description	Values
Pests	Barley: We follow Östman et al. (2003) and measure initial aphid pest density in aphids/day units with 5, 7.5, and 10 as the low/medium/high levels. Oilseed rape: We follow Zhang et al. (2017) and measure initial pest density in flea beetles per trap day units. Wheat: We follow Zhang et al. (2018) assumed aphids/tiller in their low, medium, and high scenarios.	Low: 5. Medium: 7.5. High: 10.
$NE_{Presence}$	A scalar in the range 0 – 1 representing the presence of natural enemies. Results were simulated for values from 0.01 (representing 99 % reduction in natural enemy presence) – 1.00 (complete presence of natural enemies) with intervals of value 0.10 to illustrate 10 % changes in natural enemy presence.	0: Absent 1: Present
$REA_{Change,wheat}$	This parameter is a vector of 1,000 percentage changes in the number of aphids given the presence of natural enemies, using data from Schmidt et al. (2004). We drew 1,000 Monte Carlo samples each normally distributed with the mean given from the control and treatment conditions, and the standard deviation calculated from the standard error. We then calculated the percentage change from control to treatment and bound it to [0, 1].	– Number of field sites (sample size): 32 – Number of aphids in their control condition: 366 (27) – Number of aphids in their treatment condition: 83 (7.60) – Percentage change: 77.32 %
$REA_{Change,Barley}$	This parameter is a vector of 1,000 percentage changes in the number of aphids in the presence of natural enemies in barley crops that were organically managed, using data from Caballero-López et al. (2012). Values here are for *S. Avenae* and *R. Padi* combined. We drew 1,000 Monte Carlo samples each normally distributed with the mean given from the control and treatment conditions, and the standard deviation calculated from the standard error. We then calculated the percentage change from control to treatment and bound it to [0, 1].	– Number of field sites (sample size): 72 – Number of aphids in their control condition: 67.80 (16.07) – Number of aphids in their treatment condition: 32.20 (10.38) – Change: 47.49 %
$REA_{Change,OSR}$	This parameter is a vector of 1,000 percentage changes in cabbage stem flea beetles in the presence of natural enemies in oilseed rape crops using data from Dainese et al. (2017). We drew 1,000 Monte Carlo samples each normally distributed with the mean given from the control and treatment conditions, and the standard deviation calculated from the standard error. We then calculated the percentage change from control to treatment and bound it to [0, 1].	– Number of field sites (sample size): 36 – Number of pests in their control condition: 137.94 (0.39) – Number of pests in their treatment condition: 77.17 (0.23) – Change: 44.06 %
PestDensity	Realised pest density calculated using initial pest density, natural enemy presence, and crop-specific effect of natural enemies on pests elicited from the structured literature search. The resulting value is a distribution of 1000 values.	$PestDensity = (1 - (REA_{crop} * NE)) * Pests$
$Yield_{loss,Wheat}$	Wheat-specific percentage change in yield response to pest density (Zhang et al., 2018) using field trials.	$Yield_{loss,Wheat} = 4.5\ln(PestDensity) - 5.5$
$Yield_{Loss,barley}$	Barley-specific percentage change in yield response to pest density (Ostman et al., 2003) using field trials.	$Yield_{Loss,barley} = 12.70 PestDensity_{days}^{0.65}$
$Yield_{Loss,OSR}$	Oilseed rape-specific percentage change in yield response to pest density (Zhang et al., 2017). Note, this is derived using expert elicitation.	$Yield_{Loss,OSR} = PestDensity * f(Mean, SD)$ Mean change: 13.20 % (SD: 9.90)
Field management strategy	Three alternative strategies for spraying fields. Indicative crop-specific proportion of fields using each field management strategy. Source: DEFRA (2022), c.f., Zhang et al., 2018.	Never-Spray: 0.70 % wheat, 0.9 % barley and oilseed rape Economic threshold: 37 % all crops Always-spray: ~62 % all crops
Threshold	The level of insect pests at which a field managed using economic threshold strategy would apply insecticides. The threshold level is compared to the pest density after accounting for the effects of natural enemies. Sources: Ostman et al. (2003), Zhang et al. (2017), Zhang et al. (2018), for barley, oilseed rape, and wheat respectively.	Barley: 5 aphid/days Oilseed rape: 5 flea beetles per trap days Wheat: 5 aphids/tiller
Lost value	Produces an upper bound value for the total loss. Yield and price data from DEFRA (2022). Note that yield loss percentage varies with field management strategy, and economic-threshold fields may incur additional spraying costs.	$LostValue_{PerHectare,Crop} = (Yield_{PerHectare,Crop} * Price_{PerTonne,Crop}) * Yield_{Loss,Crop}$
Total loss	The lost value per hectare multiplied by number of hectares. Area planted per crop reported annually by DEFRA (2022).	$TotalLoss_{Crop} = (LostValue_{PerHectare,Crop} * Area_{ThousandsHectares,Crop})$
Costs	There are other factors affecting farmers variable costs per hectare. John Nix farm management pocketbook (Nix, 2021).	Annual mean costs for: Wheat: £264.46 Barley: £195.41 Oilseed rape: £229.04

population of arthropod natural enemies (predators and parasitoids) to evaluate their combined effect on pest populations, rather than modelling individual natural enemy species. Generalising across natural enemies is supported by Dainese et al. (2017) finding additive effects of the presence of both parasitoids and ground beetles on suppressing pests in the oilseed rape system. While we do not have suitable data to investigate intra-guild predation of different natural enemies that feed on others, Dainese et al. (2017) results suggest that greater natural enemy diversity is likely to be complementary and increase predation of pests. Using 10 % increments allows us to report both marginal and near-complete loss scenarios. Consistent with Zhang et al. (2018), we highlight a marginal 10 % change in natural enemy populations as a realistic change from the baseline. However, in Section 3.1 we also report a much larger 50 % change as an indicative value for substantial population declines.

The first step was to estimate the effect of natural enemies on pest abundance. We found three sufficiently similar studies that reported sufficient data; Schmidt et al. (2004) for wheat, Caballero-López et al. (2012) for barley, and Zhang et al. (2017) for oilseed rape. From their estimates, we used the mean and standard errors (converted to standard deviations with sample sizes) reported to generate a distribution of estimates for the control, and treatment conditions of each paper. The percentage change from the control and treatment conditions is then reported as the REA_{Change} parameter, which is a 1,000-element vector. This Monte Carlo approach propagates uncertainty through to our estimates, allowing us to report confidence intervals.

The second step estimated how crop yields responded to different pest densities. We used empirical estimates of crop-specific yield change functions from the structured literature search (Fig. A1, supplementary information). These functions are crop specific to reflect differences in yield response to pest damage (Coston et al., 2023). The provenance of each crop yield function is reported in Table 1. As yield may be influenced by multiple factors, our analysis produced an upper bound estimate for how pests affect these crops. For simplicity of analysis, the yield functions assumed no changes in normal weather, timing of arrival, or duration of stay. As we lacked information on specific pest-predator

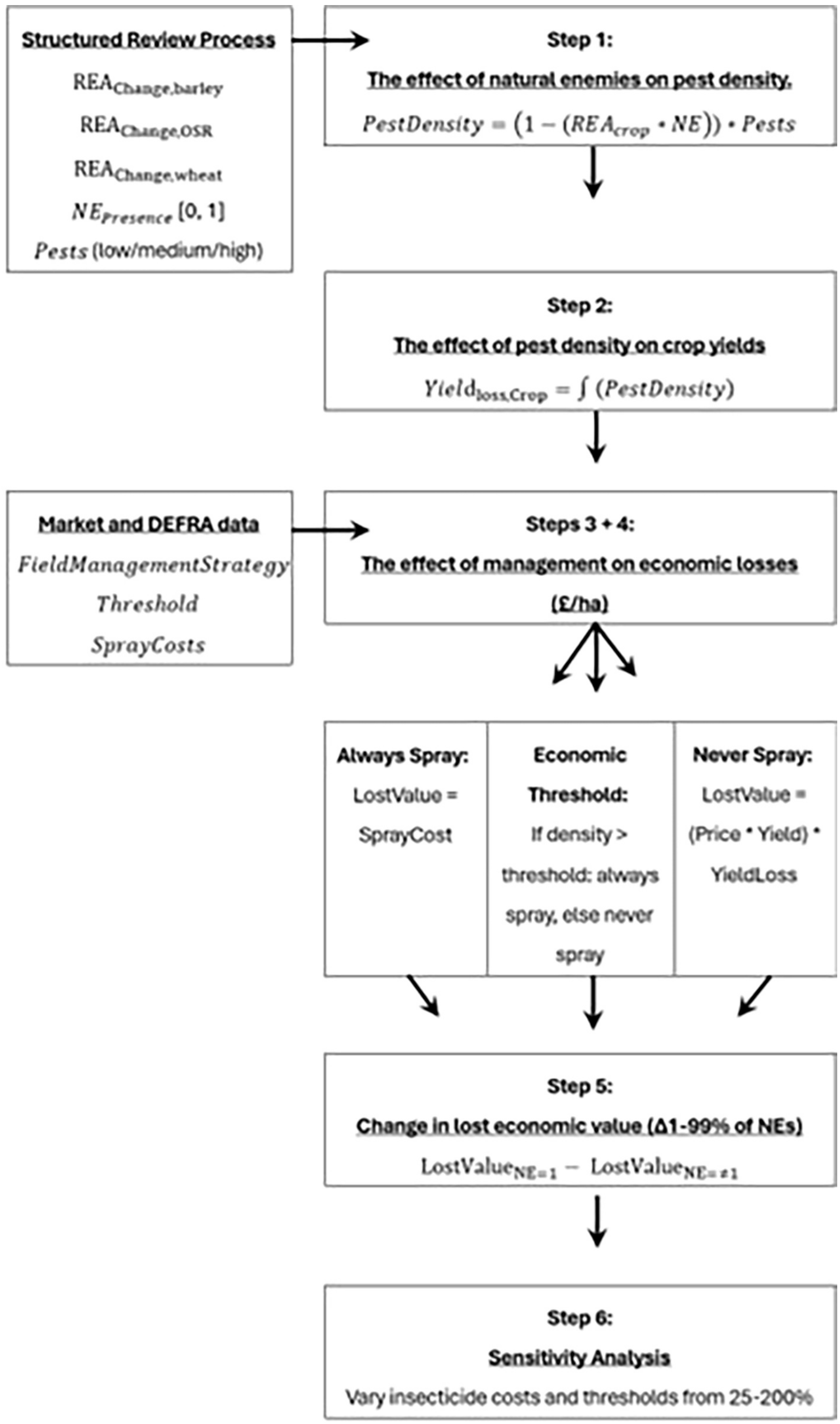

Fig. 1. Illustrative flowchart mapping the inputs and steps to our production function model. R code to replicate the function is publicly available.

interactions, we simulated yield responses at varying levels of a generalised natural enemy, which avoided potentially non-linear interactions between competing natural enemies but also limited our generalisability to any specific pest- natural enemy system.

The third step estimated the lost economic value per hectare at a UK scale. We calculated the lost value as the yield multiplied by the unit price scaled by the percentage yield lost, which required crop-specific data on average and total yield, prices, and volumes. The average value for the unit prices and yields in the decade 2011:2021 in the UK was sourced from annual DEFRA reports (Table 2). We used 2011:2021 as the most recent years with complete validated data. We did not include temporal dynamics, such as whether stopping insecticide application means increased natural enemy populations in subsequent years, as the data generated from the structured review process did not allow this level of precision (Ostman et al., 2002). Instead, we used the annual prices and yields to describe the value of pest regulation that a full presence of natural enemies would have provided if they had been present in these years. This is a conservative estimate that assumes that natural enemies are presently optimally effective and no increase in their abundance or diversity will influence yield. Although some data on imports/exports is available, integrating price dynamics into the calculation of pest regulation benefits would obscure our focus on the effect of changes in natural enemies on yield losses. Table 2 displays summary statistics for the most recent period for three crops at a UK scale.

2.2.3. Field management

The fourth stage followed Zhang et al. (2018) assumption of three sets of control costs relevant to three different strategies that farmers could choose for the management of their fields; never spraying, always-spraying, and spraying only if pest density exceeds a pre-defined economic threshold (e.g., Zhang and Swinton, 2012). We do not support one approach over another, instead we assume that these are three plausible field management strategies that farmers may adopt and then illustrate how the benefits of pest regulation vary by choice of strategy and thus approach to the application of insecticides.

Under a never-spray strategy, the threshold for insecticide application is effectively infinite as farmers do not apply insecticides (Zhang et al., 2018). Although this does not preclude the possibility of large yield losses, it also limits control costs. By contrast, following the always-spray strategy effectively has an application threshold of zero. This approach has the most certainty about losses and is easiest to forecast and predict for farm management. Essentially then, farmers trade off the potential benefits from improving natural enemy presence, for greater certainty about crop yield losses. Always spraying insecticides may be a cost-efficient prevention strategy if integrated pest management is costly, and pest outbreaks lead to potentially catastrophic yield loss as particularly relevant for oilseed rape (Williams et al., 2010). Moreover, if neighbouring farmers are assumed to spray, then always spraying may reduce the likelihood of spillovers, such as migrating pests (Rand et al., 2006; Woodcock et al., 2016). As we did not recover the timing or weight of insecticides applied, or the days in the growing cycle that pests arrive and are present in the crops, there was uncertainty around the size of potential spillover effects. We, therefore, conducted a sensitivity analysis around the control costs to better understand how variations in these factors may influence yield losses. Finally, the economic-threshold strategy applies no sprays unless pest abundance is observed to exceed pre-determined economic thresholds (e.g., Zhang and Swinton, 2012). Thus, fields managed this way will incur the costs of spraying insecticides (Table 2) only if pest abundance is above threshold levels and will not incur spraying costs at lower levels. The threshold level is a function of multiple criteria including the crop injury potential, plant resistance/tolerance, and economic value of damages (Higley and Pedigo, 1993; Ramsden et al., 2017). To improve fidelity, we used data on crop-specific thresholds from the literature (Table 1). Although Ramsden et al. (2017) critically reflected that many thresholds are without clear empirical support, where possible, we used economic thresholds from empirically supported research (e.g., Zhang et al. (2018) for the wheat crop-system), and for robustness, demonstrate how results varied across thresholds being considered.

Table 2
Annual area planted, yield achieved, harvest volume and market prices per each main crop of interest. Market data sourced from DEFRA: (https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2022/chapter-7-crops). Insecticide data sourced from John Nix Farm Management pocketbook series for 2011 to 2021 (Nix, 2021).

Crop	Area 1000 s of hectares	Prices Real terms price per tonne	Volume Thousands of tonnes	Yield Tonnes per hectare	Sprays Real terms cost of all sprays per hectare. Only relevant to always-spray or economic threshold fields.
Barley	1136.64	182.31	6895.36	6.06	£195.41/per hectare
Oilseed rape	585.74	416.96	2015.36	3.40	£229.04/per hectare
Wheat	1790.94	194.00	14194.09	7.91	£264.46/per hectare

The nominal and real value of the control costs per crop were recovered from the annually published John Nix farm management pocketbook (Nix, 2021). Although we estimate the pest regulation benefits across all three field management strategies, we also recovered the estimated percentage of fields managed in each way from DEFRA (2022) and Zhang et al. (2018) using the reported proportion of organic fields. We followed the standard assumption in the pest regulation literature (e.g., Ostman et al., 2002; Zhang et al., 2018) and assumed that insecticide application was 100 % effective at eliminating pests. As this assumption is less relevant for oilseed rape since the banning of the highly effective neo-nicotinoid sprays and absence of similarly effective sprays (Lundin, 2020), we demonstrated how the benefits of pest regulation vary with (always-spray) and without (never-spray) applying insecticides. While Conservation Biological Control (Begg et al., 2017) often involves the application of selective insecticides (Torres and Bueno, 2018), we focused on habitat management as the basis of natural enemy populations as the literature review did not recover sufficient empirical estimates to parameterise the non-target impacts of broad-spectrum insecticides on natural-enemy populations. Although selective insecticides can reduce such non-target effects, we also lacked empirical estimates for their costs, application rates, or efficacies to include them. Future extensions that incorporate parameters on the non-target mortality and economics of both broad-spectrum and selective insecticides could improve model fidelity.

The fifth and final step of the production function was to compare the lost value per hectare at 100 % natural enemy presence to scenarios with reduced natural enemy presence. The change in lost value at different levels represented the value provided by natural enemies. By scaling the presence of natural enemies down to near-complete absence, we estimated the lost value of pest regulation due to reduced natural enemy populations. While supporting more natural enemies is not cost-neutral as supportive habitats may be substituted from arable land (e.g., Garratt et al., 2017; Kleijn et al., 2019; Morandin et al., 2016), we did not recover any data on the cost of measures used to increase natural enemy populations so could not perform a full cost-benefit analysis of this farming strategy.

3. Results

3.1. Change in lost yield per hectare

Fig. 2 illustrates the change in economic losses compared to a scenario with 100 % natural enemy presence. The value of pest regulation provided by natural enemies is the change in lost value when their presence is diminished. The underlying estimated percentage change in yield lost per crop, field management strategy, and initial pest density is reported in Fig. B1 (Supplementary Information).

For the never-spray strategy, a marginal 10 % reduction in natural enemy density from a full community, i.e., 1 to 0.9, reduced yields by 10.12 % – 15.89 % (worth £39.99 – £63.11 per hectare) for barley, 2.60 % – 5.23 % (£2.76 – £5.29 per hectare) for oilseed rape and 0.03 % – 0.55 % (£0.08 – £2.72 per hectare) for wheat, respectively. These estimates were sensitive to both initial pest density and natural enemy presence. Indeed, to illustrate the value of pest regulation under a more substantial decline we also estimated the value of a 50 % reduction in natural enemy presence from a full community. The value of lost yield rose to £122.97/ph – £193.5/ph for barley, £13.37/ph – £26.78/ph for oilseed rape, and £1.15/ph – £35.52/ph for wheat, showing the high economic cost in yield loss associated with large-scale losses of natural enemies. Higher initial densities of pests, such as are possible under the never-spray strategy, were associated with higher yield losses at every level of natural enemy presence, although the value of their losses is limited by choosing to have no insecticide spray costs. By contrast, higher natural enemy presence corresponded to lower yield losses, although the shape and slope of the curves varied by crop and initial pest density. We show that reducing natural enemy presence by 50 % (from 1.00 to 0.50 on the X-axis) leads to substantial yield losses in monetary terms. A near-complete loss of 99 % of natural enemies (from 1.00 to 0.01 on the X axis) may be associated with even larger losses. In the positive scenario whereby, each 10 % restoration of natural enemy populations is associated with increased pest regulation benefits.

We assumed that the always-spray strategy reduces the possibility of any yield lost as farmers who follow this strategy prefer to incur the insecticide application cost over the potential for any nonzero yield loss. Therefore, the modelled value of pest regulation in these fields is zero. We assumed that the value of the always-spray strategy remained flat at zero change in lost yield, not because there was no lost value, but because increasing natural enemy presence provides no additional benefit in this management strategy. Although the always-spray strategy had zero variation in yield loss due to the assumption of complete insecticide efficacy, always spraying is potentially inefficient as it foregoes benefits of increased pest regulation from natural enemies and ignores long-term risks of insecticide resistance.

Under the economic-threshold strategy, insecticides are only applied if pest density exceeds a threshold. When natural enemy presence suppresses pests below a threshold, the yield loss is the same as the never-spray strategy. However, at a relatively lower natural enemy presence, farmers incur insecticide application costs. We thus illustrate a kink in the relationship between value of lost yield and natural enemy presence after an economic threshold is reached. This is most evident for barley where, depending on initial pest density, there was zero yield loss after an economic threshold for applying insecticides was exceeded. Losses were only reduced when natural enemy presences increase sufficiently that pest densities fell below the economic thresholds. This effect was least pronounced for wheat, possibly as yield losses from insect pests in wheat were always lower. The location of the kink did not always exist, such as for the low pest density in barley, but demonstrated that the benefits of economic threshold management may be larger than the always spray strategy at low natural enemy densities. The same kink was also observed for oilseed rape, but only for a medium pest density where a low density incurred very low losses, and a high density was always above the economic threshold. The economic benefits of pest regulation provided by natural enemies in oilseed rape systems were thus much more contingent on initial densities and threshold levels.

The shaded areas in Fig. 2 represent uncertainty around our estimates. There was no variance in estimates for the always-spray strategy as the economic value was always the cost of applying insecticides. By contrast, the variance for other strategies was dependent on pest density and natural enemy levels. Specifically, the largest shaded areas, representing uncertainty associated with the modelling, occurred when pest density was high with low natural enemy presence, reflecting the limitations of available field data in such conditions. Furthermore, low pest densities are typically associated with less variance, represented through smaller shaded areas, as the range of potential yield losses is much lower compared to high densities where catastrophic losses are technically possible. Near-complete losses of natural enemy presences, modelled here as up to 99 %, may cause significant yield losses of more than 20 % with costly economic implications. Fig. 2 demonstrated that the yield response depended on crop and field management strategy.

Although farmers who follow the always spray strategy appeared to not suffer direct losses from increased pest presence, it obfuscates potential long-term costs, including the development of alternative insecticides and increased yield losses. Although we do not recover dynamic data on resistance development from our structured literature search, incorporating such costs would be an important, data-intensive extension of our approach.

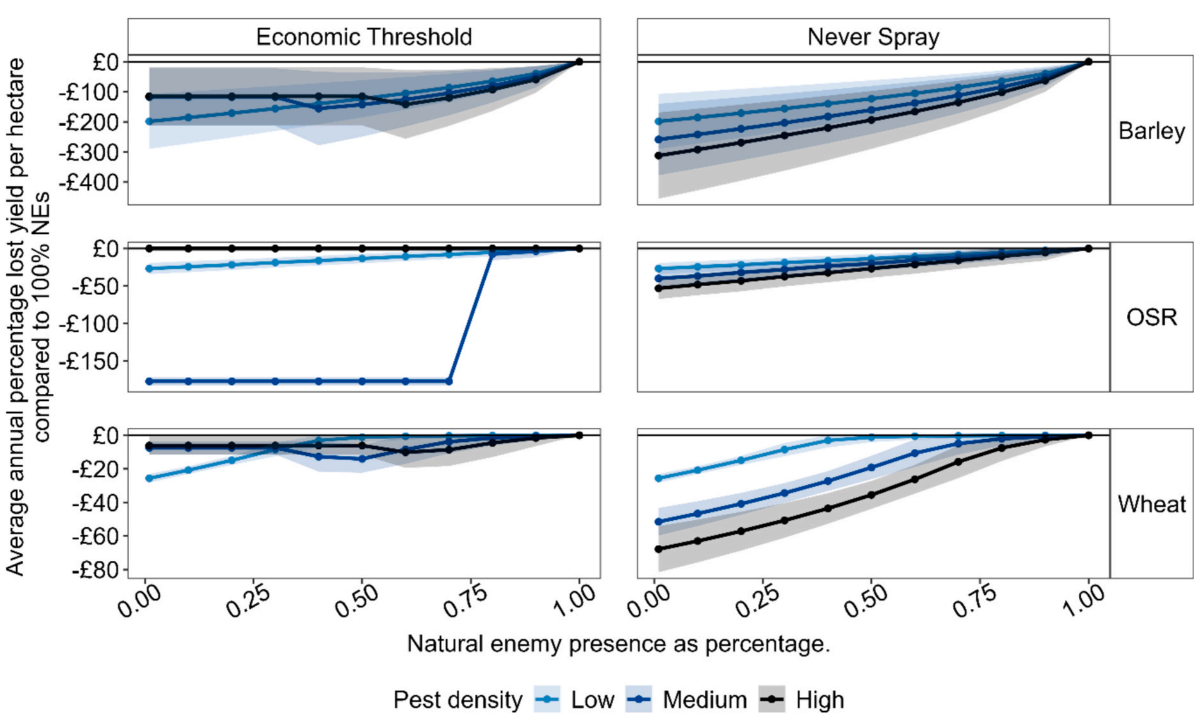

Fig. 2. Change in lost yield per hectare at different levels of natural enemy presence, pest density, field management strategy, and crop. Scaled against estimated lost yield at 100% presence of natural enemies. Uncertainty represented by shaded areas calculated as +/- one standard deviation around the plotted lines.

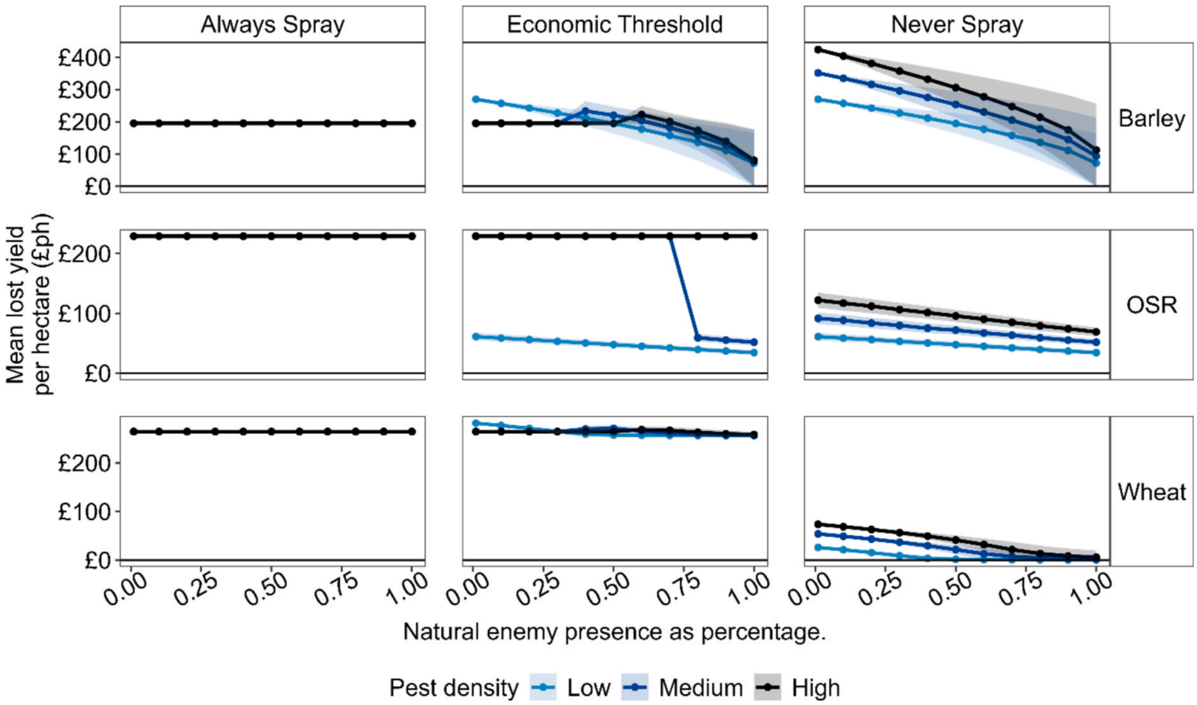

Fig. 3. Total estimated losses per hectare. Variation between crops partly due to different insecticide application costs per crops. The shaded areas are crop and pest density specific and are calculated as the mean +/- one standard deviation to represent areas of uncertainty around point estimates of the losses per hectare.

3.2. Value of lost yield per hectare

In Fig. 3 we illustrate the absolute value (in £/HA) of potential losses per hectare for each crop, pest density, level of natural enemy presence, and field management strategy. Across all of these, estimated lost crop yield for a 10 % reduction from a full community of natural enemies were valued per hectare between £108.98 – £171.13 for barley, £36.93 – £73.97 for oilseed rape, and £0.74 – £9.60 for wheat. In Section 3.3, we perform sensitivity analysis of these estimates to changes in insecticide costs and thresholds, demonstrating the robustness of our findings.

The losses per hectare for the never-spray strategy could be lower than other field types, but these strongly depend on initial pest densities and presence or absence of natural enemies. Losses for the economic-threshold strategy were also sensitive to pest and natural enemy densities which affect whether insecticide application costs were incurred alongside yield losses. For the economic-threshold strategy, increased natural enemy presence can reduce pest pressure below the threshold and reduce the value of lost yield. The always-spray strategy incurred insecticide costs regardless of natural enemy presence, with cost variations driven solely by differences in application timing across crop rotations.

3.3. Sensitivity analysis

To evaluate how the value of lost yield responded to changes in the costs of insecticides and their thresholds for application, we performed sensitivity analysis for the economic-threshold fields. In Fig. 4, we show that when thresholds for application are lower, the total losses were more predictable as insecticide was applied more often under the economic-threshold strategy. However, at higher thresholds, insecticide application was less likely and thus the losses were more sensitive to the pest pressure. At “Default”, the thresholds were the same as the default assumptions. At 25 % and 50 % of the normal threshold (“lowest”, and “low” respectively), results at lower thresholds more closely resembled those where fields were managed by always spraying insecticides and benefits were less sensitive to changes in natural enemy presence. Conversely, 150 % and 200 % of the normal threshold (“high” and “highest”), appeared more like those fields that followed the never-spray strategy and realised larger benefits from increasing natural enemy presence. The shaded areas and different curves across pest densities indicate that higher thresholds lead to higher uncertainty. However, we again highlight the uncertainty in our estimates through the observable shaded areas.

In Fig. 5, we show that for economic-threshold fields, reductions in insecticide costs are associated with larger losses as farmers change to use insecticides. Conversely, increases in costs also change field management behaviour. We varied the cost of insecticides from 25 % (“lowest”), 50 % (“low”), 100 % (“default”), 150 % (“high”), and 200 % (“highest”) of the insecticide costs we used to better understand how the benefits of pest regulation vary with insecticide application costs for the economic-threshold strategy. We only plotted the losses per hectare for this strategy as their fields were sensitive to changes in insecticide costs. We demonstrate that reductions in insecticide costs are associated with larger losses as farmers change to use insecticides; increases in costs also change behaviour.

A final robustness check is to compare our results against Zhang et al. (2018) who studied the wheat crop system in a region of the UK using the economic surplus approach. They found that the annual value of pest regulation for the wheat crop was £0-2.3million (standard deviation of £0.4mn) over an annual average wheat area of 233 thousand hectares. Scaling their estimate to the size of our study area produces an annual value of £9.87 (£8.15 – £11.59) per hectare, comparable to our estimates of value in fields that are never sprayed, and which have low initial pest density. Although we used a different approach to valuation, we produced comparable estimates showing the positive economic value of pest regulation provided by natural enemies in the UK.

4. Discussion

The aim of this study was to evaluate the economic value of pest regulation provided by natural enemies in the UK for three major arable crops: barley, oilseed rape, and wheat. Using a production function with parameters drawn from the literature, we incorporated natural enemy

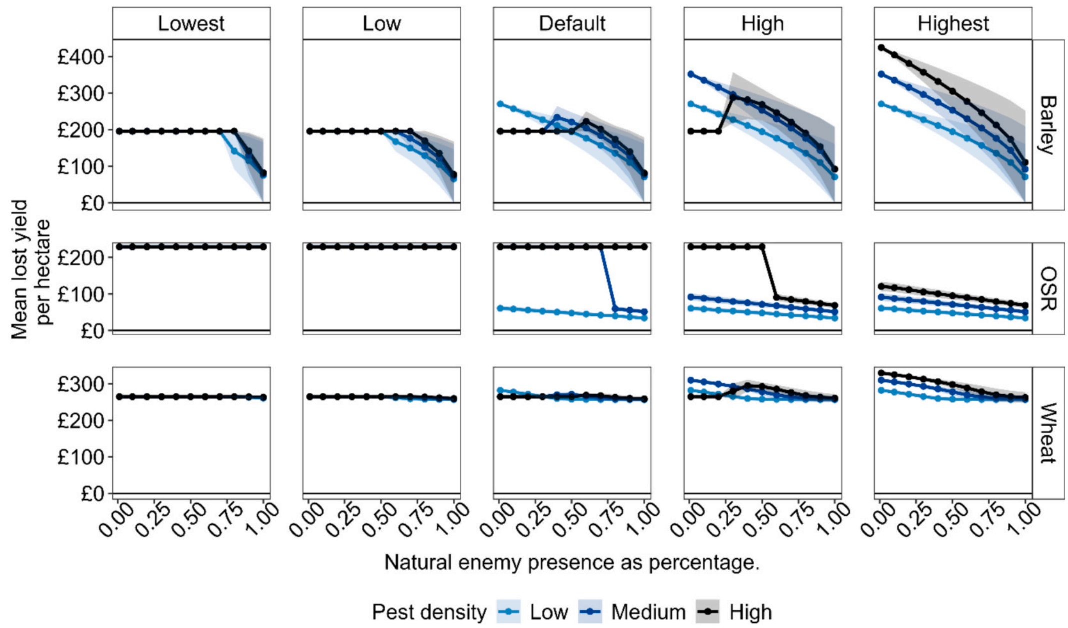

Fig. 4. Estimated economic value of lost yield per hectare by crop, pest density, and levels of economic thresholds. Estimates for economic threshold fields only. The facet labels correspond to 25 % (lowest), 50 % (low), 100 % (default), 150 % (high), and 200 % (highest) of our default crop-specific thresholds. Higher thresholds increase uncertainty and potential benefits from natural enemies. The shaded areas represent uncertainty as they are calculated as the mean +/- one standard deviation.

effectiveness, pest densities, and field management strategies to estimate economic impacts. Our results are threefold: (a) significant data gaps remain in pest- natural enemy relationships across these crop systems, (b) uncertainty is higher at lower natural enemy densities, and (c) increasing natural enemy presence consistently yields economic benefits. A 10 % reduction in natural enemies resulted in estimated yield losses of £111.33–£174.84 per hectare for barley, £36.92–£74.26 for oilseed rape, and £0.49–£8.34 for wheat. These estimates were more precise at lower pest densities or high natural enemy presence, but varied by crop, economic threshold, and field management strategy. Our results show that increasing natural-enemy presence generates meaningful per-hectare economic benefits, while declines may be costly as farmers substitute from biocontrol to purely applying insecticides.

While our analysis focused on Conservation Biological Control via habitat management (e.g., enhancing floral resources, maintaining hedgerows), it is important to recognise that efforts to reduce chemical use can include the use of selective insecticides that are designed to target pests while minimising harm to their non-target natural enemies thus preserving their pest regulation service (Torres and Bueno, 2018). Many modern insecticides are designed to target pests while preserving

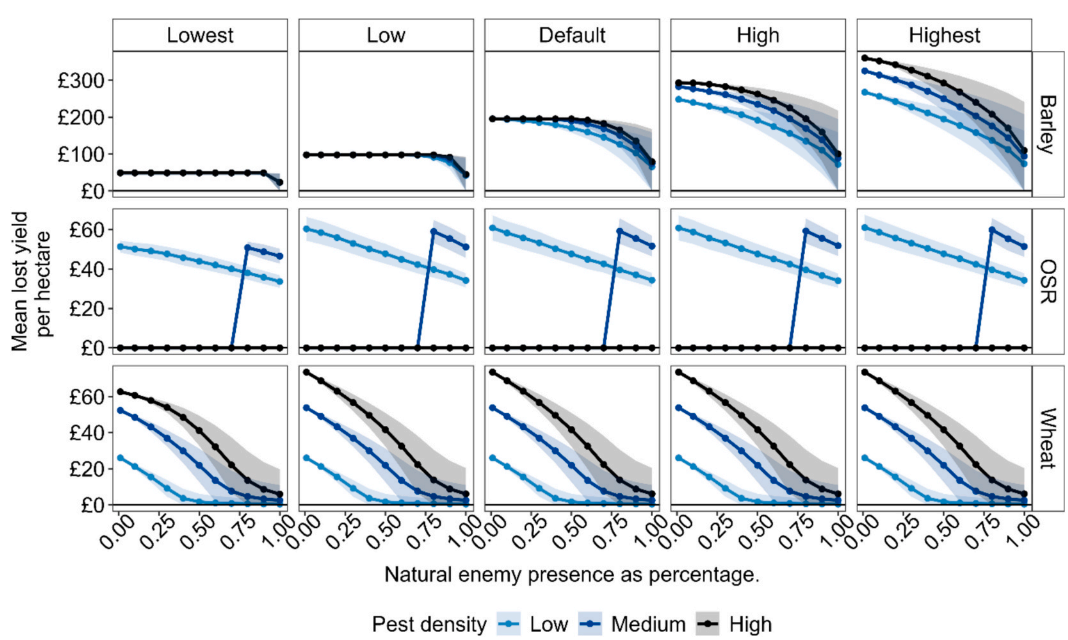

Fig. 5. Estimated mean economic value of yield lost per hectare at different levels of insecticide application cost. Estimates for economic threshold fields only. The facet labels correspond to 25 % (lowest), 50 % (low), 100 % (default), 150 % (high), and 200 % (highest) of the observed spray costs. The shaded areas are the mean estimate +/- one standard deviation to represent uncertainty.

beneficial species, making them a potentially powerful tool in integrated pest management (IPM) frameworks (Li et al., 2021). This form of Conservation Biological Control is already in practice across many agricultural systems (Begg et al., 2017) and may be more readily adopted by growers accustomed to chemical interventions. Although the costs of insecticide inputs are relatively straightforward to estimate, the impacts on natural enemies are poorly understood making it difficult to fully quantify the economic trade-offs of pest control strategies. Future work could use the general framework developed here to explore the economic value of selective insecticide use in supporting natural enemy populations and sustaining pest regulation services.

Our findings indicate that the presence of natural enemies may yield notable economic benefits, consistent with Ostman et al. (2003) in the barley system, and with Zhang and Swinton (2012) who found a significant dollar/hectare value of natural enemies being present in their soybean system. Further, in the wheat system, Zhang et al. (2018) found that there was a positive marginal value in introducing natural enemies, but this depended on initial pest densities. Further, our results indicate economic thresholds for insecticide application were more often exceeded at higher initial pest densities, making chemical control more likely than conservation biological control through habitat management. Estimating the value of insect pest control across increasing natural enemy densities, rather than just presence/absence, better reflects the ability of natural enemies to provide pest regulation services and represents an advantage of our production function approach. Our result, that increasing natural enemy densities can have significant economic benefits on yield (e.g., Lundin et al., 2020), was consistent with Letourneau et al. (2015) who found larger losses of economic surplus from a reduction of natural enemy species richness from high to low levels compared to a reduction from high to medium levels. However, as our production function used data from experimental work testing how the number of pests responds to introducing additional natural enemies to the system, our results were more uncertain (larger standard deviations) at very low densities of natural enemies. Consequently, future experiments with low natural enemy densities in field conditions could enhance the precision of economic valuations of conservation biological control.

Our sensitivity analysis indicated that the value of insect pest regulation depended on the field management strategy that could farmers adopt and their respective economic thresholds. We departed from Zhang and Swinton (2012) and Daniels et al. (2017) whose models only considered whether fields were organic or not and instead followed Zhang et al. (2018) in delineating between three types of field management strategy that farmers could follow: never spraying or organic, economic thresholds, and always spraying insecticides. The never-spray strategy was, unsurprisingly, likely to suffer larger yield losses when natural enemy populations decline (e.g., Ostman et al., 2002). Although the never-spray or economic-threshold strategies were susceptible to larger losses of yield, they realised the most benefits from increasing the presence of natural enemies. Indeed, Zhang et al. (2018) found that the economic benefits of pest regulation were higher when a greater proportion of farmers followed economic thresholds. Our results were consistent to sensitivity analysis that varied the economic thresholds for each crop. The always-spray strategy had no variation in annual costs and did not incur short-term insecticide application costs and, according to our bioeconomic model, it may be economically better than other field management strategies in specific conditions. However, the always-spray strategy did not benefit from increasing natural enemy populations and would be open to negative long-term effects of reduced insecticide efficacy or limits on their application (Coston et al., 2023; Dainese et al., 2017; Ostman et al., 2002). In reality, the always-spray strategy is unlikely to completely eradicate pest damage. Some pests may be harder to control, for example there is a declining availability of conventional chemical insecticides resulting from deregistration and resistance in key cereal pests to the remaining compounds. For example, *Psylliodes chrysocephala L.* (cabbage stem flea beetle) is a major UK pest of winter oilseed rape and following the withdrawal of neonicotinoid seed treatments, an over reliance on pyrethroids has led to high levels of pyrethroid resistance and difficulty controlling this pest. The occurrence of resistance in a field that followed the always-spray strategy could result in an uncontrolled explosion of pest populations due to the absence of natural enemies (Ong and Vandermeer, 2023). Together, our results indicate that natural enemies can provide valuable pest regulation services in fields that permit them, although the exact value depends on insecticide application thresholds.

Although prior work has investigated which measures may be effective in increasing natural enemy populations (Nilsson et al., 2016; Power et al., 2016), the economic feasibility of interventions such as planting hedgerows remains unclear (Garratt et al., 2017). For instance, Morandin et al. (2016) demonstrated that hedgerows can enhance both pest regulation and pollination services, but the extent to which individual farmers capture these benefits can be limited by spatial spillovers to neighbouring farms (Boetzl et al., 2023; Garratt et al., 2017). Furthermore, the economic benefits of such interventions may take several years before increased yields from enhanced pollination and pest regulation can offset the initial costs of implementation and the opportunity cost of lost production (Kleijn et al., 2019; Morandin et al., 2016). Although we lacked data for a full cost-benefit analysis of natural enemy-supportive interventions, our study provides estimates of the economic value of biological control that can be incorporated into future cost-benefit analyses of habitat interventions. Integrating pest regulation benefits into future assessments may strengthen the case for sustainable pest management strategies.

Our results suggest that following an always-spray strategy may provide more predictable future returns as yields are unresponsive to pest or natural enemy density. However, this approach precludes farmers from realising any economic benefits from increasing natural enemy presence or incurring costs from population declines. Our results, therefore, suggest that the total national value that natural enemies provide in pest regulation may be limited by the low adherence to biological control methods. Although we assumed that the always-spray strategy suffered no crop pest damage, i.e., 100 % insecticide efficacy, given the application of precautionary sprays, our results for the never-spray strategy provide plausible estimates for a scenario where insecticide efficiency was less than 100 %. As such the always-spray strategy may still suffer lower levels of pest damage, especially if pests develop resistance. Moreover, we could not consider whether spraying insecticides also affected natural enemies, due to absence of relevant field data, suggesting that future work with sufficient data on these added factors may improve the fidelity of our estimates to the realities of the farming system.

The preliminary step for our production function was a literature review intended to reveal knowledge gaps on the parameters used within the economic modelling. However, the review also highlighted a wide range of opportunities for future research. For example, there was no validated model directly linking pest density to yield loss in oilseed rape; although Lundin et al. (2020) linked pest density to crop injury and separately crop injury to yield loss. Even within the comparatively well-studied crop systems of wheat and barley there are still questions at each of the four steps in our production function. These concern ecological factors (Lundin et al., 2012; Dainese et al., 2017, Naranjo et al., 2015), economic thresholds (Lundin et al., 2020; Ramsden et al., 2017), and market data which is rarely spatially or temporally disaggregated to allow more granular analysis (Zhang et al., 2018). The absence of data is not new; Lundin et al. (2012) argued that lack of information on yield losses and efficacy of control measures limited the development and implementation of integrated pest management, and Letourneau et al. (2015) discussed limitations of existing ecological data on field conditions relevant to economic thresholds. Finer resolution of spatial data, through crop cover maps, could also provide more granular modelling of field types and pest densities (c.f., Boetzl et al., 2023). Opportunities for future fieldwork to reduce uncertainties include better understanding the efficacy of natural enemies on pests (e.g., Zhang and Swinton, 2012), the effect of different control measures on pest species (e.g., Lundin et al., 2012), the relationship between plant injury and yield (e.g., Lundin et al., 2020), efficacy of new, non-neonicotinoid insecticides, the development of resistance in target species, and how that translates to yield losses (Williams et al., 2017), the interrelationship between climate and landscape factors on pest density (Boetzl et al., 2023), and the connection between pest control strategies and yield responses (Dainese et al., 2017). Further field evidence on these factors can reduce uncertainties around the economic value of biological control (Zhang et al., 2017).

5. Conclusion

We show that natural enemies provide significant economic benefits to UK agriculture through pest regulation services. By integrating ecological data into a production function model, we provided a UK-wide estimate of the economic contribution of natural enemies across wheat, barley, and oilseed rape, improving on previous regional estimates. Our study incorporates multiple crops, broader pest- natural enemy interactions, variations in field management, and sensitivity analysis around insecticide costs and thresholds, to provide a more comprehensive assessment of the economic value of biocontrol. However, notable data gaps, particularly regarding pest- natural enemy interactions at lower natural enemy densities, introduces uncertainty into our estimates. Addressing these gaps through targeted field studies and long-term monitoring could improve the precision of future valuations and strengthen evidence-based pest management policies. Our results suggest that while biological control introduces greater uncertainty compared to chemical pest control, it also creates opportunities to reduce input costs and enhance yields by leveraging natural pest suppression. Further, policies that incentivise natural enemy conservation and integrate natural pest control into farm management strategies could mitigate risks from insecticide resistance. Recognising and safeguarding the economic value of natural enemies is essential for fostering more sustainable farming systems.

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CRediT authorship contribution statement

Peter King: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Theresa Robinson:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Charlotte Howard:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition. **Tom D. Breeze:** Writing – review & editing, Writing – original draft. **Martin Dallimer:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101776.

Data availability

The market data, production function R scripts, and outputs are publicly available https://github.com/pmpk20/DruidD1/. All replication materials are also available at the University of Leeds Research Data Repository here: https://doi.org/10.5518/1674.

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