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Improving the ecological and economic performance of agri-environment schemes: Payment by modelled results versus payment for actions

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ABSTRACT

Researchers and policy-makers have become increasingly interested in re-designing agri-environmental policy to improve both economic efficiency and ecological effectiveness. One idea within this debate has been payments for results (outcomes) rather than payment for actions. Payment for result policies have been argued to have some important advantages, but two key disadvantages are the higher risks faced by landowners, leading to low participation rates; and the potentially high costs of monitoring outcomes. Bartkowski et al. (2021) propose an alternative of payment for modelled results, which claims to avoid these two problems. Our paper provides the first application of this approach to spatially realistic patterns of ecological and economic heterogeneity for farmland biodiversity in England. We compare payment for modelled results findings with approximately equivalent payment for actions schemes intended to deliver increases in the same biodiversity indicators. Key insights are that payment for modelled results delivers superior predicted ecological outcomes for the same budgetary cost as payment for actions, whilst economic surpluses to farmers are also higher.

1. Introduction

Agri-Environment Schemes (AES) have been mainstreamed in agricultural policies across the globe as a means to financially incentivise farmers to undertake nature-protecting activities and to mitigate environmental damage (Batáry et al., 2015; Prager, 2015). At their core, AES schemes aim to compensate land managers for the additional costs and income foregone incurred in farming with higher environmental and ecological quality standards (Tyllianakis and Martin-Ortega, 2021). However, evidence is emerging world-wide that the dominant design of AES – payment for actions – often fails to achieve desired environmental outcomes, such as halting the decline of farmland biodiversity (Bertoni et al., 2020; Pe'er et al., 2020; although see Walker et al., 2018).

Payments for actions, alongside results-based payments, sit within the general class of incentive-based AES and are the two main policy design alternatives that have been analysed (Derissen and Quaas, 2013; Wuepper and Huber, 2022). Payment for action schemes offer farmers a (typically uniform) payment for adopting defined management practices within a specified region or nation state (Engel, 2016). These actions – such as reductions in fertilizer use, or reductions in stocking rates – are intended to achieve an environmental policy target, such as an improvement in river water quality or an increase in the population of a farmland bird species. In contrast, results-based payment schemes offer payment conditional on achieving a specified ecological outcome, creating an incentive for those farmers who can provide the ecological benefit at a low cost to join the AES (Chaplin et al., 2021; Birge et al., 2017; Gibbons et al., 2011). Within Europe, the majority of AES schemes are action-based, partly because of the assumption that these contracts are easier to monitor and may be considered fairer than results-based alternatives (White and Hanley, 2016). However, interest is growing in the use of results-based incentives as part of the on-going reforms of the Common Agricultural Policy (Herzon et al., 2018; Wuepper and Huber, 2022; Hasler et al., 2022) and the re-design of land use policy in the UK post-Brexit.

A key drawback of many action-based schemes is that payments do not reflect the spatial heterogeneity in economic costs and potential ecological benefits, which significantly hinders the cost-effectiveness of such schemes in achieving an ecological target. Furthermore, paying for

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specific actions does not allow farmers to make use of private information they may hold on how best to produce the desired environmental output (Wätzold and Drechsler, 2005). Consequently, payments for results schemes are being increasingly discussed in the academic literature and policy circles in Europe and the UK as a promising alternative.

From a theoretical perspective, results-based payments are often considered to be potentially more cost-effective than action-based payments (White and Hanley, 2016; Derissen and Quaas, 2013). Payment-for-result schemes have a number of advantages over payment-for-actions AES policies, which are that (i) society pays for the desired results, rather than the actions intended to produce these results, (ii) farmers have an incentive to innovate to reduce the private costs of producing the contracted-for results, whilst (iii) farmers can use private information to determine how best to produce these results (Burton and Schwarz, 2013; White and Hanley, 2016). Monitoring costs could be higher or lower than payment for action schemes, depending on the relative observability of effort versus outcomes. However, a key concern of payments for results is that such schemes transfer risk from the buyer (the government) to the seller (farmers), since farmers cannot be sure that a particular set of actions will deliver a particular result (Russi et al., 2016; Bartkowski et al., 2021). Many factors determining ecological outcomes such as a change in populations for a specific bird species are out with farmers' control (for example the weather; the behavior of neighbors; migration patterns) (Fleury et al., 2015). This means that payment for result schemes may have lower participation rates than equivalent payment for action schemes.

Recent reviews show that few "pure" payment for outcome schemes operate in Europe (Tanaka et al., 2022). This is potentially due to the perceived problems of low participation due to the relatively higher risk to farmers (compared to payment for action schemes), and high monitoring costs for the regulator (Herzon et al., 2018). Bartkowski et al. (2021) offer a novel solution to these twin problems which they call "payments by modelled results". Payments would be made to farmers based on predicted environmental results using a model-based online decision support tool. Farmers choose between different bundles of actions which deliver a specific modelled outcome in terms of the regulator's environmental target (such as a reduction in nitrate levels in a river). From the farmer's perspective, the risks associated with such a contract are lower than the risks of a pure payment for results contract, since the farmer willingly contracts to undertake a set of actions from a portfolio of options which the model predicts will yield the desired environmental outcome. From the regulator's perspective, monitoring costs are lower than with a pure payment for results, since the payment for each farmer is based on the predicted rather than actual outcome. Of course, over time, the regulator must check that the model does a good job of making predictions.

In this paper, we develop an ecological-economic model to test the performance of this "payment for modelled results" policy, comparing it with a standard payment for actions policy designed to achieve the same environmental target. Moreover, we compare both of these policies with what we refer to as a hybrid policy, which uses a more flexible or spatially-differentiated payment for actions approach. This hybrid approach is intended to capture, in a simple, realistic way, the spatial heterogeneity in biodiversity outcomes associated with this farm management action. This is important, since a key advantage of payment for results (or modelled results) policies over payment for actions is their ability to reflect the underlying spatial variability in the ecological productivity of land with respect to the targeted environmental outcome. We compare ecological and economic outcomes of all three policies based on a fixed overall policy cost to the regulator. As far as we are aware, this paper is the first application of the payment for modelled results approach to spatially-realistic patterns of ecological and economic heterogeneity for farmland biodiversity in England.

There are relatively few empirical studies that examine payment for results schemes. A systematic review by Nthambi et al. (2022) identified 31 studies exploring payment for results schemes in Europe. The majority of the studies covered stakeholder discussions with farmers on how best to design schemes. These discussions focused on how to measure outcomes, including the indicator choice (e.g. Birge et al., 2017), how to determine sufficiently high levels of payment to achieve target levels of participation (e.g. Wezel et al., 2016), how to structure these payments (e.g. Fleury et al., 2015), as well as the advice, support and training needed to implement a payment for results scheme (Wezel et al., 2018) and the use of nudges to improve predicted uptake (Massfeller et al., 2022).

Chaplin et al. (2021) provide one of the few studies comparing action and results-based schemes. The environmental performance of two objectives was measured: provision of winter bird food for farmland birds, and provision of pollen and nectar resources for pollinating insects in arable farming systems. Results showed that the payment by results measures were more effective than a conventional payment for actions AES. In addition, farmers' self-assessment of results (environmental outcomes) was highly correlated with the experts' assessment of the results, although it should be noted extensive training was undertaken with farmers on the monitoring of the intended results. Wuepper and Huber (2022) compare an action-based scheme with a results based scheme in Switzerland, and find that both the conservation outcome and return on investment was higher for the results-based scheme. However, neither of these papers evaluate the modelled results policy option proposed by Bartkowski et al. (2021), which is the principal objective of the present work.

2. Methods

2.1. Conceptual approach

Consider a region where land can be divided into two possible uses which are mutually exclusive at any point in time: agriculture and conservation. Within such a setting, it is assumed that there are a n number of landowners (agents) who each manage a single 1 km by 1 km (100 ha) land parcel. We assume that agents maximize profits from land use for each parcel. This profit maximization is subject to a number of constraints, including that land that is currently designated for conservation (eg as a protected area) must be managed for conservation. The agent's default land use for agricultural land parcels is assumed to be for agricultural purposes in the form of crop or livestock production. However, agents can choose to enrol land parcels in an AES that delivers ecological benefits and receive a set payment for this. The agent's optimization problem entails maximizing the profits derived from agricultural production plus the value of enrolling in the AES. Every hectare enrolled in the AES means one less hectare for agricultural production. Therefore, the cost to the agent of enrolling in the AES is the opportunity costs of the foregone agricultural output, measured as the gross margin per hectare. Additionally, there is variability in the quality of agricultural output across the landscape. Ranking land parcels along this gradient yields a continuous, upward sloping supply (marginal cost) curve for enrolling land parcels into the AES. The agent maximizes profits by choosing to enrol land parcels where the marginal cost of enrolling the land parcels (i.e., lost agricultural profit at the margin) is less than the payment offered under the AES.

Across the landscape, the number land parcels that can be enrolled by agents into the AES is constrained by the budgetary cap of the regulatory authority, implying that there is a maximum number of land parcels that can be enrolled into the scheme. Consequently, the regulatory authority aims to design a scheme that is both economically cost-effective and ecologically effective. The regulatory authority defines the ecological target(s) that the AES is designed to achieve, and depending on the type of AES implemented, defines a specific change in management which will switch the land use from agriculture to conservation. Finally, there is heterogeneity in land parcel's ecological quality across the landscape, measured in terms of each parcel's ability to support the ecological target, even with a land use change from agriculture to conserved status.

Using this framework, we compare the economic and ecological performance of a payment for modelled results AES with a payment for actions policy designed to achieve the same ecological target. In addition, we compare both of these policies with a hybrid policy, which uses a more flexible or spatially differentiated payment for action approach.

2.1.1. Payment for actions AES

Under a payment for actions AES, the regulatory authority pays agents to undertake the prescribed land management practice. Agents are paid per hectare of agricultural land enrolled in the scheme and are expected to undertake the prescribed preferred land management action. Under this design, there is no ecological quality weighting in terms of the land parcel's suitability of supporting the ecological target. As a result, the ecological target may increase, decrease, or remain the same within the enrolled land parcels, despite parcels being converted from agriculture to the preferred land management practice. However, since agents have undertaken the prescribed action, they will receive payment regardless of the ecological outcome.

We assume that agents are profit maximizers and are expected to enrol land parcels where the AES payment offered per hectare exceeds the agricultural gross margin per hectare. Consequently, land parcels with the lowest gross margins are more likely to be enrolled in the AES. Where there is a positive correlation between agricultural gross margins and the suitability of the land parcel for the ecological target, we expect there will be minimal benefits to the ecological target, as the most ecologically-beneficial parcels will not be enrolled. In contrast, where there is a negative correlation between agricultural gross margins and the suitability of the parcel to support the ecological target, parcels which offer the highest benefits to the ecological target are more likely to be enrolled in the scheme (as these are of the least opportunity cost to the agents).

2.1.2. Payment by modelled results AES

In the payment by modelled results AES, the agent receives a payment based on the predicted (modelled) increase in the ecological target on land parcels enrolled into the AES. The agent undertakes the same prescribed land management practices as the payment for actions AES but receives the payment per unit increase in the ecological target, rather than the number of agricultural hectares enrolled. By modelling each land parcel's ability to support the ecological target, land parcels now have an ecological weighting. As with the payment for actions scheme, we assume that agents are profit maximizers and agents are expected to enrol land parcels where the AES payment offered per unit increase in the ecological target exceeds the agricultural gross margin per hectare of the agricultural land switched to the new land management practice.

Agents with higher-value agricultural land parcels that are predicted to deliver substantial increases in the ecological target will receive a higher payment under the modelled results scheme than payment for actions. As such, they are more likely to enrol in the payment by modelled results AES than the payment for actions. In landscapes where there is a negative correlation between the agricultural gross margins and the parcels' ability to support the ecological target, we expect there to be minimal differences in ecological outcomes when comparing a payment for actions and payment by modelled results scheme.

2.1.3. Hybrid payment for actions AES

The regulatory authority pays agents who undertake prescribed land management practices that benefit the ecological target on enrolled agricultural land parcels. However, under the hybrid scheme, agents receive a top-up payment reflecting landscape-level, non-agricultural features which ecological modelling shows to be important co-determinants for the ecological target. Consequently, in landscapes where there is a positive correlation between agricultural gross margins and the land parcel's suitability for the ecological target, the spatially differentiated policy is likely to result in greater increases in the ecological target than the uniform payment for actions policy.

2.2. Case study region, ecological target and preferred land management practice

We apply our ecological-economic model to a UK case study region known as the Tees Valley, Pennine Uplands and North York Moors (Fig. 1). The case study region covers an area of approximately 5400 km^2 and encompasses a range of habitats and land use types from upland moors in the west of the region, low-lying agricultural land throughout the central region and increasing urbanization in the east at the coastal margin. The case study boundary represents an example of the continuum of lowland-to-upland farming systems which is broadly representative of many locations within the UK where support through agri-environment payments has been very important historically (eg Dallimer et al., 2009). Agricultural systems in the upland areas are characterized by low-intensity livestock farming, principally hill sheep and beef cattle. Studies have shown that farming within the upland areas of the case study is intrinsically unprofitable without considerable external support from agri-environment schemes (Tooze et al., 2021). Farming in the lower-lying eastern parts of the case study region is focused on arable and dairy. An example of the agricultural land classifications is shown in Fig. 1, Panel C.

Alongside agricultural land, undeveloped areas contain a mosaic of biodiversity-rich habitats including semi-natural grasslands that are subject only to low-intensity use, wetlands, marshlands and heather uplands, some of which are protected through conservation designations (Fig. 1, Panel B). The region encompasses three Special Protection Areas (SPAs) designated under the EU Birds Directive and three Special Areas for Conservation (SACs) designated under the EU Habitats Directive. Coastal habitats of the Teesmouth and Cleveland Coast SPA are classified for the assemblage of over 20,000 overwintering waders, including Eurasian curlew (*Numenius arquata*), Northern lapwing (*Vanellus vanellus*) and oystercatcher (*Haematopus ostralegus*) (JNCC, 2020). In spring and summer, the UK's largest terrestrial National Nature Reserve, Moor House-Upper Teesdale, supports lapwing, curlew and oystercatcher who move to the uplands for their breeding season (JNCC, 2020).

Our ecological target for our three AES schemes is an increase in adult lapwing abundance, although we also model the effects of each AES policy on "off-target" species (curlew and oystercatcher). Lapwing appears on the Red-List (species in most urgent need of conservation action) in the UK (Eaton et al., 2015), and populations have declined by 54 % in the UK in the past 50 years, partly due to changing farmland management. Lapwing tolerates the widest variety of grassland conditions and are found nesting in a range of different habitat types from spring-sown crops to former opencast sites (North East Nature Partnership, 2023). Outside the breeding season, the species frequents a wide variety of habitats including large, cultivated fields, wide expanses of grassland, lake or river margins and estuaries (European Commission, 2010). Consequently, our preferred land management practice within the AES policy is defined as a switch from arable production or intensive livestock farming to what we term low-intensity grassland management (Rowland et al., 2017). Costs associated with grassland conversion from arable land are minimal, typically involving soil cultivation and seeding only. Ecological modelling shows that lapwing can benefit from a switch in these production methods to low-intensity grassland (Simpson et al., 2022). In making such a switch, farmers give up the profits from livestock or crop production in a specific grid square, and earn zero farm profit from low-intensity grassland. Instead, they derive a reward for this conservation action through the AES payments being modelled.

Consequently, the case study region offers us a chance to test alternative AES designs for a farmed landscape that is heavily dependent on additional farm payments, and where species of interest have been negatively affected by changing farmland management practices.

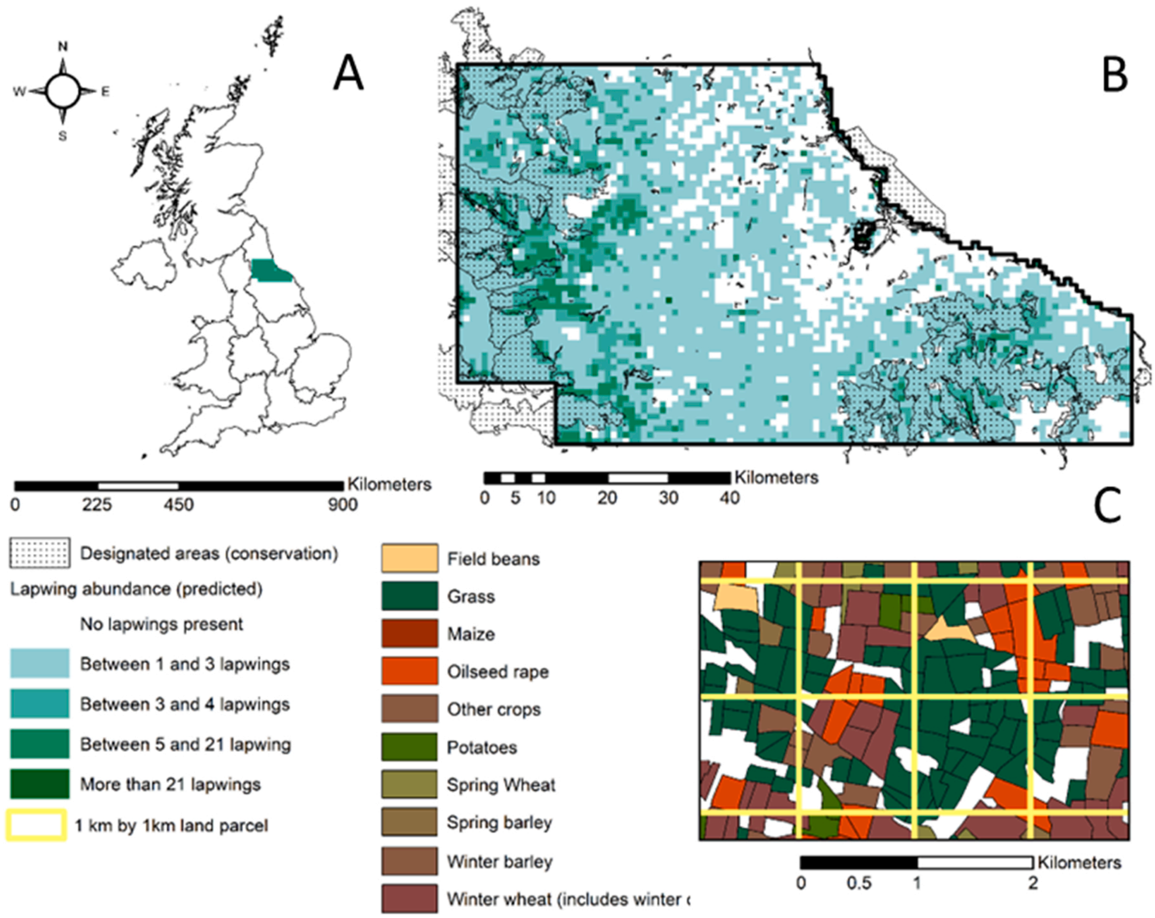

Fig. 1. Location of the Tees Valley, Pennine Uplands and North York Moors case study (A); predicted lapwing abundance across the case study region under current last use, overlayed with conservation designations (B) and a snapshot of the agricultural landscape at the 1 km by 1 km grid scale (C).

2.3. Empirical approach

Our empirical approach consists of three stages. Firstly, an ecological regression model predicts the current abundance of lapwing for each 1 km by 1 km land parcel across a case study region, based on current land use. This provides us with a baseline to compare to the ecological performance of the three alternative AES. Secondly, this ecological model is used to estimate *potential* changes in lapwing abundance as a result of agents undertaking the preferred land management action: a switch from agricultural production to low-intensity grassland. Finally, economic simulation models integrate data on agricultural values within the landscape to determine the profitability of each land parcel under the alternative AES policies compared to current cropping or livestock production. From this, we can predict which agents would sign up for (i) a payment for actions scheme (ii) a hybrid, spatially targeted payment for actions scheme and (iii) a payment for modelled results scheme. We then analyse these decisions spatially to understand the resulting impacts on both habitats and species, and the likely economic effects on farmers.

2.3.1. Data development

As a baseline, we take the current land use structure in the case study region covering 5400 km^2. This is divided into 5280 land parcels equalling a size of 1 km x 1 km, aligned to the Ordnance Survey British National Grid. Each land parcel contains data from three spatially referenced datasets covering land classification, crop distribution and wading bird abundance and distribution. Where possible datasets from 2016 are utilized.

2.3.2. Land classification

Each land parcel comprises of any combination of 30 distinguished land use types and crop classifications derived from the Centre of Ecology and Hydrology (CEH) Land Cover Map (LCM2015) and Land Cover plus Crops map (Rowland et al., 2017). This produced 21 broad classifications following the UK Biodiversity Action Plan Broad Habitats classes including urban, improved grassland, arable and horticulture. Using the CEH Land Cover plus Crops map, arable and horticulture was further sub-divided into 11 crop types (beet, field beans, grassland, maize, oilseed rape, potatoes, spring barley, winter barley, spring wheat, winter wheat (including oats) and other).

2.3.3. Agricultural gross margin

The gross margin for any agricultural activity is defined as the per-hectare revenue minus the variable costs associated with producing that output. For crop data, crop coverage per hectare was derived from the Land Cover plus Crops map and multiplied by the corresponding crop gross margin data per hectare from the SRUC Farm Management Handbook (Beattie, 2019). Gross margin values are given for each crop type per ha on a productivity range from low, medium to high yield. To account for differences in yield, data on soil quality at the 1 km by 1 km resolution was derived and linked to the crop distribution. For livestock, data was sourced from the England Agricultural Census which details the number of livestock by type at the 5 km by 5 km grid resolution. Using the livestock gross margin values from the SRUC Farm Management Handbook, the total gross margin for all livestock at the 5 km by 5 km resolution was calculated. This was then disaggregated to the 1 by 1 km resolution. The spatial variation in the agricultural gross margin values is shown in Fig. 2.

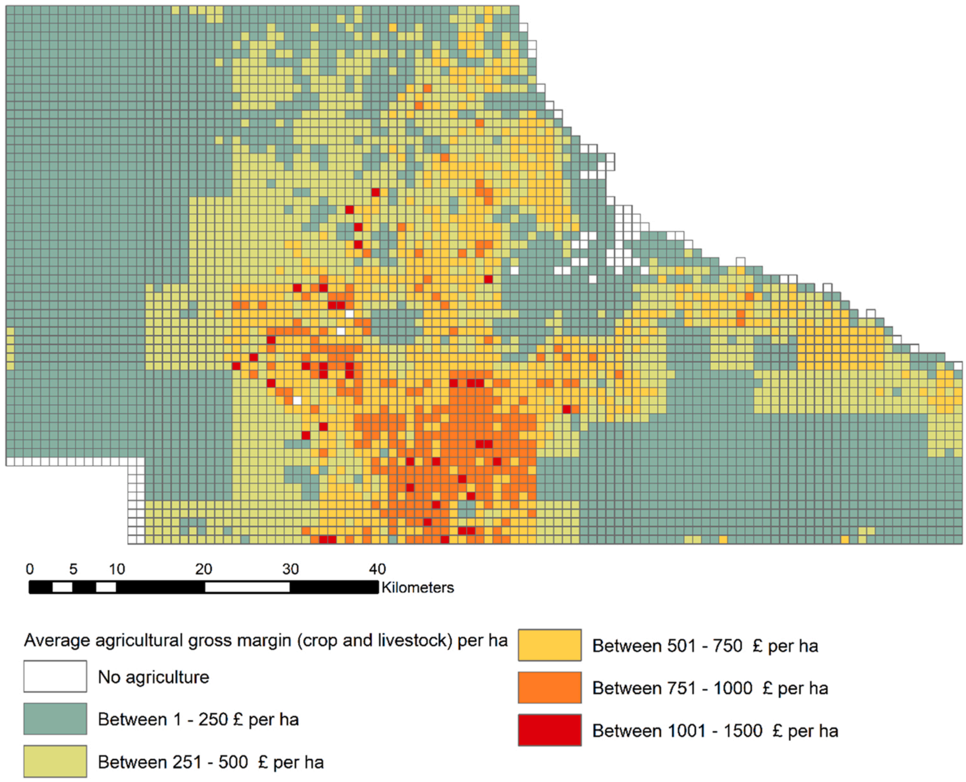

Fig. 2. Average agricultural gross margin (£ per ha) for each land parcel across the case study landscape.

2.3.4. Ecological model

Bird abundance data was not readily available for all land parcels within our case study region and as a result, we developed a Species Abundance Model (SAM) for lapwing, our species of interest, as well as for curlew and oystercatcher. SAMs generate predictions of abundance for unsampled locations in a study area using existing data from other sample areas, extrapolating this to new areas based on environmental characteristics (Barker et al., 2014). The development of these ecological models allowed us to obtain predictions for the species abundance under current land use and also as a result of changing land management practices (required for the economic modelling).

Lapwing, curlew and oystercatcher data were sourced from the British Trust of Ornithology (BTO) Breeding Bird Survey (BBS) which counts adult birds on a stratified random sample of 1 km by 1 km parcels aligned with the Ordnance Survey British National Grid. We developed our ecological model using a sample of 1798 land parcels for the eastern region of the UK to ensure that data were more directly relevant to our study system, given the known regional differences across the UK for bird distributions.

The data collected by the BBS survey has been widely used in ecological modelling to predict species distribution and abundance nationally (Balmer et al., 2013) and for regional and landscape-scale studies. Given that it is repeated through time, it also allows for a robust analysis of how bird distributions and abundances change through time (for examples see Renwick et al., 2012; Hewson et al., 2016; Higgins and Crick, 2019). It is widely considered one of the most robust biodiversity monitoring datasets globally (Magurran et al., 2010).

Explanatory variables for the ecological modelling were chosen based on the existing literature for predicting bird habitat suitability (Brotons et al., 2004; Tattoni et al., 2012) and the requirements of the economic aspect of the modelling approach. Our SAM used a negative binomial model from within the generalized linear model framework (GLM). The models were fitted by minimizing the negative log-likelihood using the minimization procedure (glm2) in the software package R (Version 3.6.2). The best model was selected by comparing the AIC values (Burnham and Anderson, 1998). Models with the smallest AIC value are considered the best model. The model was also evaluated for a sub-sample of the 2016 data set which was independent of the dataset used in the primary modelling.

The results (Table 1) highlight that lapwing abundance was significantly reduced on land parcels containing agricultural crops. Subsequently switching from agricultural production to improved grassland could benefit lapwing, dependent on other environmental factors within the 1 km by 1 km land parcel (Table 1). Lapwing also responded negatively to urbanization and pylon density.

The final version of the SAM allowed us to make predictions for lapwing abundance for all land parcels within the case study landscape under current land use. Further to this, we can use the SAM to predict those land parcels that offer the most opportunity for increased lapwing abundance if agricultural land parcels are converted to low-intensity grassland. Thus, for each land parcel, we have two predicted lapwing abundances, the first is the species based on the current land use, and the second based on all land parcels currently being farmed for crops or livestock grazing being switched to low-intensity, zero profit grassland.

2.3.5. Economic model

To enable us to explore the ecological and economic landscape outcomes of the alternative AES we need a payment for modelled results policy that aligns with the payment for actions policy. We achieve this by setting the budgetary spending of the three alternative policy options to be roughly equal. The regulator sets a budget limit, or cap on the total cost of the AES for the region (in our case £1.6 million). This cap allows us to derive the alternative payment rates for the three AES we wish to compare (Table 2). This constraint was implemented by calibrating all three policy options to have approximately the same overall budgetary cost of £ 1.6 million per year across the whole case study area.

Our payment-for-actions policy is equivalent to the dominant type of contact under Pillar 2 of the Common Agricultural Policy, which we set as the restoration or creation of low-grazing intensity grassland. To ensure additionality, this change in land management practice in the

Table 1
Results of SAM negative binomial model for predicting lapwing, curlew and oystercatcher abundance in the Eastern UK.

VARIABLES		Lapwing model		Curlew model		Oystercatcher model	
		Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
UK Broad Habitat Classifications	Acid Grassland (area ha)	-0.036***	-0.009	0.003	-0.011	-0.023***	-0.009
	Bog (area ha)	-0.043***	-0.01	0.001	-0.011	-0.024***	-0.009
	Broadleaf woodland (area ha)	-0.081***	-0.011	-0.053***	-0.012	-0.041***	-0.01
	Calcareous grassland (area ha)	-0.036**	-0.016	0.023	-0.017	0.002	-0.017
	Coniferous woodland (area ha)	-0.074***	-0.01	-0.021**	-0.011	-0.033***	-0.009
	Fen, marsh and swamp (area ha)	-0.005	-0.013	-0.037	-0.034	-0.022	-0.014
	Freshwater (area ha)	-0.048***	-0.013	-0.025*	-0.014	0.011	-0.011
	Heather (area ha)	-0.038***	-0.01	0.004	-0.011	-0.023**	-0.009
	Improved Grassland (area ha)	0.028	-0.009	0.002	-0.011	-0.01	-0.009
	Heather grassland (area ha)	-0.035***	-0.01	0.008	-0.011	-0.011	-0.009
	Inland rock (area ha)	-0.130***	-0.038	-0.097***	-0.027	-0.053***	-0.016
	Littoral rock (area ha)	-0.646***	-0.177	0.088	-0.149	0.283***	-0.093
	Littoral sediment (area ha)	-0.168***	-0.05	0.023	-0.024	0.076***	-0.022
	Neutral grassland (area ha)	0.036	-0.035	0.048	-0.043	-0.037	-0.048
	Saltmarsh (area ha)	0.029*	-0.017	0.063***	-0.023	0.047***	-0.016
	Saltwater (area ha)	-0.086***	-0.019	0.013	-0.015	0.004	-0.013
	Suburban (area ha)	-0.100***	-0.012	-0.079***	-0.014	-0.031***	-0.009
	Supralittoral rock (area ha)	0.082	-0.159	-0.543*	-0.321	-0.118	-0.152
	Supralittoral sediment (area ha)	-0.048***	-0.015	-0.044**	-0.022	0.003	-0.011
	Urban (area ha)	-0.078***	-0.015	-0.068***	-0.019	-0.064***	-0.012
Crop classifications	Beets (area ha)	-0.019	-0.013	-0.072	-0.046	0.002	-0.014
	Field Beans area ha)	-0.039***	-0.012	-0.040**	-0.019	-0.061***	-0.017
	Maize (area ha)	-0.027*	-0.015	-0.043	-0.028	-0.089***	-0.019
	Oil Seed Rape (area ha)	-0.048***	-0.01	-0.032***	-0.012	-0.054***	-0.011
	Potatoes (area ha)	-0.032**	-0.014	0.027	-0.026	0.014	-0.012
	Spring Barley (area ha)	-0.049***	-0.012	-0.003	-0.013	0.004	-0.01
	Spring Wheat (area ha)	-0.034***	-0.011	-0.01	-0.013	-0.006	-0.01
	Winter Barley (area ha)	-0.040***	-0.012	-0.024*	-0.014	-0.016	-0.012
	Winter Wheat (area ha)	-0.052***	-0.01	-0.045***	-0.013	-0.042***	-0.009
	Other crop type (area ha)	-0.030***	-0.01	-0.033**	-0.013	-0.020**	-0.01
Additional explanatory variables	Pylons Density (density of electricity pylons within the land parcel)	-0.336***	-0.117	-0.445***	-0.116	-0.375**	-0.155
	Tidal (distance of land parcel from nearest tidal boundary km)	0.013***	-0.004	0.015***	-0.003	-0.002	-0.003
	Watercourse (distance of land parcel from nearest tidal boundary km) (distance km)	-0.409***	-0.085	-0.232**	-0.091	-0.401***	-0.087
	Model year dummy: 0 = 2016, 1 = 2017	0.051	-0.101	-0.02	-0.091	0.013	-0.103
Constant		4.350***	-0.902	0.771	-1.053	1.644*	-0.853
Observations		3620		3626		3610	
chi2		3.776		835.6		525.4	

* ** $p < 0.01$, * * $p < 0.05$, * $p < 0.1$.

Table 2
A summary of the payment rates for the three alternative AES policies.

AES Policy	Payment Rate
Payment for actions: low intensity grassland restoration	£ 585 per hectare
Payment by modelled result: predicted increase in lapwing abundance	£ 12,800 per modelled lapwing increase
Spatially differentiated payment for actions (Hybrid policy):	£ 585 per hectare base payment rate £ 620 per hectare if the land parcel that met the inclusion criteria of (i) no urbanization within the parcel and (ii) no electricity pylons running through the land parcel

model can only take place on agricultural land patches currently farmed for crops or more intensive livestock production. We assume that for a farmer to be willing to enter any AES scheme, they must be offered a subsidy payment equal at a minimum to the agricultural rent forgone. Under the payment for actions policy, the subsidy paid to farmers was calculated based on the average opportunity cost per ha of restoring agricultural land to low-intensity grassland across the case study region, this gave us a payment rate of £ 585 per hectare (1).

$$Paymentrate(ha) = \frac{Totalcrop(ha)}{Totalagriculrualgrossmargin(£)} \quad (1)$$

Our payment for modelled results scheme paid agents based on predicted increases in lapwing abundance on agricultural land parcels that switched to low-intensity grassland. We derived a payment rate of £ 12,800 per modelled increase in lapwing. We calculated this payment by first ranking the agent's opportunity cost for a predicted one-unit increase in lapwing per agricultural land parcel if it were restored to low-intensity grassland. These opportunity costs were then ranked from lowest to highest (Fig. 3). The opportunity cost varied from £ 6300 up to £ 100,300 per additional lapwing. Next, for all agricultural land parcels that could be restored to low-intensity grassland, we calculated the total amount (maximum policy cost) that all agents would need to be paid if all parcels were switched to low-intensity grassland, and the resulting total increase in lapwing abundance (Fig. 4). This allows us to identify the minimum payment a regulator would need to offer an agent to switch from agriculture to low-intensity grassland, for a specific target increase in lapwing. For example, Point A on Fig. 3 shows a regulator would need to offer a payment of £ 6331 per modelled increase in lapwing for that parcel to be enrolled in the scheme and switch from agriculture to low-intensity grassland. In contrast, the land parcel marked Point B on Fig. 3 would need to be offered £ 27,271 per modelled increase in lapwing to be enrolled on the scheme. Using this

Fig. 3. Opportunity cost per modelled lapwing increase, ranked from lowest to highest for all land parcels that could be switched from cropping or grazing land to low intensity grassland within the case study region. Note: we only include land parcels with a unit cost per modelled lapwing increase of £ 50,000 or less.

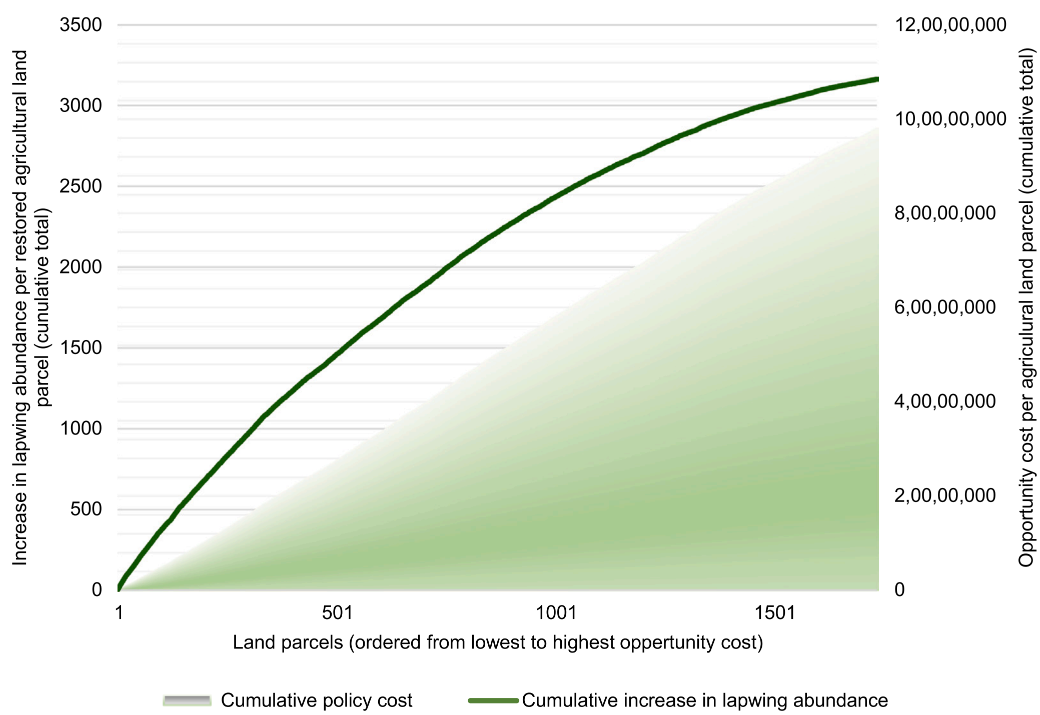

Fig. 4. Cumulative increase in predicted lapwing abundance on agricultural land parcels restored to low intensity grassland (left hand axis). Cumulative opportunity cost for agricultural land parcels to switch from agriculture to low intensity grassland (right hand axis). Land parcels on horizontal axis are ordered from lowest to highest opportunity cost.

opportunity cost curve (supply curve) for lapwing, and the cumulative policy costs (Figs. 3 and 4) we were able to estimate that for a subsidy budget of £ 1.6 million, agents could be offered a payment rate of £ 12,800 per modelled lapwing, resulting in a predicted increase of 131 in the adult lapwing population across the study area.

Under the hybrid payment for actions scheme, all agents were offered the base payment rate of £ 585 per ha to convert agricultural land to low-intensity grassland. In addition, land parcels that met the ecological inclusion criteria received an additional bonus payment. This bonus payment is for additional landscape-level, non-agricultural features which ecological modelling shows to be important co-determinants for the ecological target. For our case study region, and target species of lapwing, the SAM showed that lapwing abundance is predicted to increase in land parcels containing no urbanization and no electricity pylons overhead. Subsequently, land parcels that met the inclusion criteria of (i) no urbanization within the parcel and (ii) no electricity pylons running through the land parcel, were offered a bonus payment of an additional £ 40 per ha giving a total payment of £ 620 per ha. This additional amount of £ 40 was chosen to ensure that the total budget for the policy would be £ 1.6 million, the same as the payment for action and payment for modelled results scheme.

2.3.6. Ecological - economic model

An agent-based model was developed in Stata MP (Version 16) to model agent's choices based on the relative economic returns for switching from agricultural production to low-intensity grassland under the payment for actions, payment for modelled results and spatially weighted AES. The agent-based determines the profitability of each land parcel under the three AES and remaining in current agricultural production, taking into account the land parcel's potential suitability to support increases in lapwing abundance. Using the payment rates offered under each of the three AES, our agent-based model determines whether an agent will enrol his land parcel in the AES or remain in current agricultural land use. Using ArcGIS, we compared which parcels would be enrolled under the three AES, how the distribution of low-intensity grassland would shift and the predicted changes in the abundance of lapwing.

3. Results

3.1. Payment for actions

We find that under this scheme, 39 agents are predicted to enrol agricultural land parcels into a payment-for-action scheme to restore low-intensity grassland (Table 3). This results in the restoration of 2792 ha of low-intensity grassland at a cost to the regulator of £ 1.6 million. Under this scheme, there is a predicted 0.98 % increase in the number of lapwings. Under this design, a one-unit increase in lapwing costs the regulator approximately £ 17,945 per lapwing.

3.2. Spatially weighted payments for actions

37 agents were predicted to enrol agricultural land parcels to the spatially weighted AES. This results in the restoration of 2721 ha of low-intensity grassland and a predicted 1.08 % increase in the abundance of lapwing compared to the current landscape (Table 4). This costs approximately £ 16,300 per unit increase in lapwing.

3.3. Payment for modelled results

Agents were offered a payment rate of £ 12,800 per modelled increase in lapwing. At this rate, the agent-based model predicted that 32 agents would enrol agricultural land parcels in the AES, and this results in the restoration of 2168 ha of low-intensity grassland (Table 5). There is a 1.41 % increase in the number of lapwings above the current predicted abundance for the landscape.

To demonstrate that the predicted sign-up of agents to the payment for modelled results scheme is non-linear in the payment rate, we also modelled the sign-up rate under two alternative payment levels of £ 10,000 per lapwing and £ 15,000 per lapwing (Table 6). There is a clear step change in the participation rates at three modelled payment rates with 9 agents predicted to participate at the lowest rate (£10,000 per lapwing) and 90 predicted to participate at £ 15,000 per lapwing. This result is directly attributable to the variations in agents' opportunity costs for restoring agricultural land to low-intensity grassland and the spatial heterogeneity in predicted increases in lapwing abundance across the landscape. We calculated pairwise correlations between (i) the predicted increases in lapwing abundance for agricultural land parcels that could be restored to low-intensity grassland and (ii) the agricultural gross margin of the land parcel. We calculated these pairwise correlations for all agricultural land parcels that could be restored to grassland ($n = 2569$). For our landscape, we find a significant, positive correlation between the agricultural gross margin and the predicted increase in lapwings, $r(2569) = 0.54$, $p < 0.001$.

Table 3
Change in grassland coverage and species abundance under the payment for actions scheme.

	Total	Percentage Gain
Land parcels enrolled into the scheme	39	-
Hectares of grassland restored	2792	1.60 %
Predicted increase in lapwing abundance	91	0.98 %
Total subsidy payment for restoration of agricultural land parcels to grassland (£ GBP)	1,633,000	-

Table 4
Change in grassland coverage and species abundance under the hybrid spatially differentiated payments for action scheme.

	Total	Percentage Gain
Land parcels enrolled into the scheme	37	-
Hectares of grassland restored	2721	1.58 %
Predicted increase in lapwing abundance	100	1.08 %
Total subsidy payment for restoration of agricultural land parcels to grassland (£ GBP)	1,632,000	-

Table 5
Change in grassland coverage and species abundance under the payment for modelled results scheme.

	Total	Percentage Gain
Land parcels enrolled into the scheme	32	-
Hectares of grassland restored	2168	1.27 %
Predicted increase in lapwing abundance	131	1.41 %
Total subsidy payment for restoration of agricultural land parcels to grassland (£ GBP)	1,680,000	-

Table 6
A comparison of change in grassland coverage and species abundance under three alternative payment rates in a payment by modelled results scheme.

Payment Rate	£ 10,000 per lapwing	£ 12,800 per lapwing	£ 15,000 per lapwing
Land parcels enrolled into the scheme	9	32	90
Hectares of grassland restored	557	2169	5705
Predicted increase in lapwing abundance	40	131	339
Total subsidy payment for restoration of agricultural land parcels to grassland (£ GBP)	£ 401,000	£ 1,680,000	£ 5,000,000

3.4. A comparison of the three alternative AES scheme designs

Our final set of results compares the landscape scale outcomes in terms of farmer participation, change in lapwing numbers and change in non-target species (curlew and oystercatcher) across the three alternative AES designs (Fig. 5). The total subsidy cost to the regulator is fixed at £ 1.6 million for each of the three schemes, however, the estimated surplus to farmers participating in the schemes was greatest for the payment for modelled results AES. Under this scheme, farmers received a surplus of £ 256,000 compared to £ 131,000 under the spatially weighted scheme and £ 95,000 under the payment for actions scheme. Further to this, the ecological gains in terms of lapwing abundance are greatest under the payment for modelled results scheme, with an increase of 131 lapwings compared to 100 under the spatially weighted

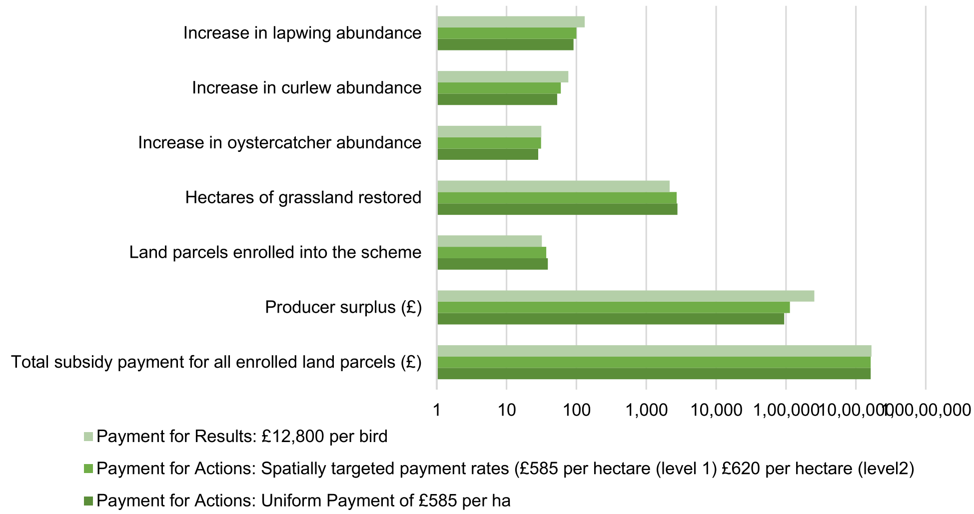

Fig. 5. A comparison of the predicted ecological and economic outcomes for the three alternative AES.

scheme and 91 under the payment for results scheme. Indeed, lapwing abundances were found to be significantly higher (*mean* =0.05, *SD* = 0.46) on parcels restored under the payment for modelled results scheme compared to the payment for results scheme (*mean* = 0.03, *SD* = 0.32 ($t(2570) = 1.67$, $p = <0.05$)). Lapwing abundances were also found to be significantly higher (*mean* =0.05, *SD* = 0.46) on parcels restored under the payment for modelled results scheme compared to the hybrid scheme (*mean* = 0.04, *SD* = 0.36 ($t(2570) = 1.35$, $p = <0.10$)). These results suggest that for this case study region, the payment for modelled results policy offers clear ecological and economic benefits over the payment for actions policies. This is directly attributable to the variations in the agent's opportunity costs for restoring agricultural land to low-intensity grassland and the spatial heterogeneity in predicted increases in lapwing abundance across the landscape. For our landscape, we find a significant, positive correlation between the opportunity cost and the predicted increase in lapwings, $r(2569) = 0.54$, $p < 0.001$.

The benefits of the payment by modelled results policy are further enhanced when we consider the predicted gains in the non-target species. Recall that within our ecological modelling framework, we can also predict the change in abundance of two further waders of ecological importance, curlew and oystercatcher. We predicted that the greatest increase in curlew abundance would also be under the payment for modelled results scheme, with an increase of 77 compared to 60 under the hybrid scheme and 53 under the payment for actions scheme. Curlew abundances were found to be significantly higher (*mean* =0.03, *SD* = 0.28) on parcels restored under the payment for modelled results scheme compared to the payment for actions scheme (*mean* = 0.02, *SD* = 0.19 ($t(2570) = 1.60$, $p = <0.05$)). However, there were no significant differences between the predicted curlew abundances under the payments for modelled results (*mean* = 0.03, *SD* = 0.28) and hybrid scheme (*mean* = 0.02, *SD* = 0.21 ($t(2570) = 1.20$, $p = <0.05$)). The increase in oystercatcher numbers was consistent across the three alternative schemes, ranging from a gain of 28 under the payment for actions scheme to 32 under the payment for modelled results scheme.

We show that there are also large differences in where restoration occurs under the three schemes with seven land parcels common to all three schemes (Fig. 6). Under the payment-for-action scheme (Panel A) restoration occurs where the opportunity costs of switching from agricultural land use to low-intensity grassland are the cheapest. These parcels are found through scattered through the central band of the case study region, north to south. The number of enrolled land parcels reduces from 39 to 37 moving from the payment for actions scheme to the hybrid scheme. Under the hybrid scheme, additional parcels enrol which are found on the fringes of the uplands (Panel B). Finally, under the payment for modelled results AES, these opportunity costs are effectively weighted by the ecological model to reflect differences in the costs per predicted increase in the target species across space, which in itself depends on a large number of factors taken into account in the ecological model. This results in a very different distribution of land parcels enrolling in the scheme, with a clear clustering of parcels enrolled on agricultural land to the edge of the Pennine uplands with the majority of land parcels also adjacent to one another.

4. Discussion

Payment for results policies have been studied by many previous researchers (Fleury et al., 2015; Birge et al., 2017; Chaplin et al., 2021). However, no empirical simulations to date have studied the likely impacts of a payment for modelled results policy. Using an ecological-economic modelling framework, we simulated the landscape scale ecological and economic outcomes of three alternative AES policies for a case study region. We compared a payment for actions policy, a hybrid spatially weighted payment for actions policy and a payment by modelled results policy, all of which were designed to benefit the same environmental target, an increase in lapwing abundance. We show that for the same overall budgetary cost, the payment for modelled results schemes yields superior outcomes in terms of biodiversity indicators than either the payment for actions or the hybrid scheme. Fewer hectares of low-intensity grassland are created under payment for modelled outcomes, but the modelled gains in lapwing populations are greater since the ecological model enables the targeting of restoration actions where the biodiversity pay-off in terms of increases in lapwing is greater. However, there are also, as a result, large differences in where restoration occurs under the three schemes. Under payment for action, restoration occurs where the opportunity costs of changing land use are lowest. Under payment for modelled results, these opportunity costs are effectively weighted by the ecological model to reflect differences in the costs per predicted increase in the target species across space, which in itself depends on a large number of factors taken into account in the ecological model. Note that the "superior biodiversity outcomes" referred to above relate solely to the bird species modelled. Less low intensity grassland created under payment for modelled outcomes could imply forgone gains in other species for which low-intensity grassland is a preferred habitat. Less low-intensity grassland creation could also mean fewer opportunities for flood alleviation or recreation (e.g. Ridding et al., 2018). The social benefits of these excluded environmental gains are not accounted for in our model outputs, or in our

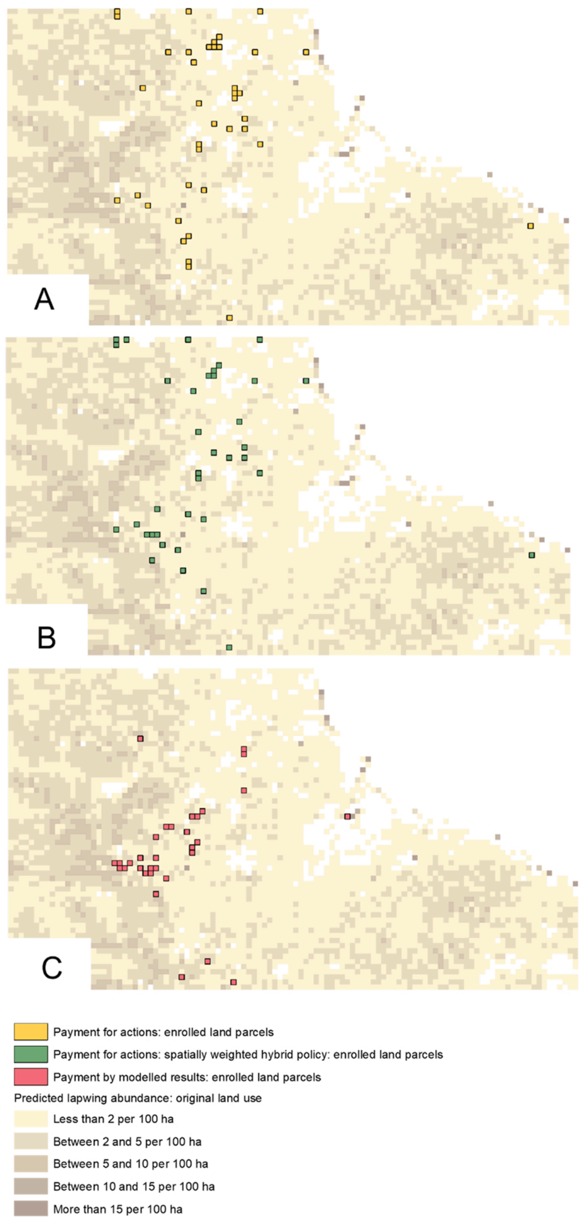

Fig. 6. A comparison of enrolled land parcels under the payment for actions scheme (A), spatially weighted hybrid policy (B) and payment by modelled results (C).

assessment of what works best.

Our paper uses an ecological-economic model to derive these simulated outcomes, showing what might happen in a given landscape for three different land use policy designs. This approach combines a statistical model relating ecological outcome (bird populations, in this case) to land use, with land use decisions being driven by a comparison of relative returns between alternative uses – typically in a spatially-explicit manner (Drechsler, 2020). The integrated ecological-economic model allows us to explore trade-offs and complementarities between changes in land use and biodiversity outcomes, and to trace out how the aggregate costs of meeting some conservation target change with both *how* this target is met and the *level* at which an ecological target is set. The specific approach taken in the present paper is an agent-based model (e.g. Schouten et al., 2013; Bell et al., 2016). This has advantages over alternatives such as optimization approaches (e.g. Groeneveld et al., 2019), since a much greater spatial resolution of model outputs is typically possible.

This set of results would seem to offer evidence in favour of the payment for modelled results suggestion put forward by Bartkowski et al. (2021). Whilst we were unable to compare outcomes with actual ecological results (since the schemes we simulate are hypothetical), it would also seem likely that payment for modelled results will encourage higher levels of participation than payment for monitored, actual, results, since the latter transfers risks from the regulator to the farmer. If farmers are risk averse, then this will reduce participation, other things being equal. As Russi et al. (2016) have noted, the implicit transfer of risk-bearing from the government (or other funder) to farmers under payment-for-results is likely to be a major factor deterring participation, yet this does not occur under payment for *modelled* results, since farmers know for certain ex ante the payment they will receive, regardless of actual (monitored) environmental outcomes.

Payment for modelled outcomes is an interesting suggestion since it retains some of the advantages of a payment for actual results policy, as argued by Bartkowski et al., whilst avoiding the problems of uncertainty for the farmer and monitoring costs for the regulator. However, paying for modelled outcomes means that one of the main advantages of the "pure" payment for results approach – that linking payments to actual environmental outcomes has the potential to harness farmers' self-interest in optimizing outcomes, thereby providing incentives for entrepreneurship in the provision of environmental goods and services – no longer holds. Farmers are instead constrained to the ecological production technology which is incorporated into the model used by advisors to generate expected ecological outcomes, rather than using their own mental models of, for example, the links between how they manage their land over time and bird populations. Moreover, we note that in our model, farmers do not choose which "technology" to use to produce more lapwings, since we constrain this to involve creation of low-intensity grassland only. This means that farmers cannot use the private information they hold on how best to produce the desired environmental outcomes – a key advantage of payments linked to actual outcomes (White and Hanley, 2016; Burton and Schwarz, 2013). A closely-related criticism can be drawn from the ideas in Gerling and Wätzold (2020). This is that, under climate change, the nature of the land management change in a specific location which works best to deliver target environmental outcome is likely to alter. A payment for actual results policy allows flexibility for farmers to respond to the changing nature of "what works best on my farm": this only holds true for payment for modelled results if the model used to relate actual management change to predicted conservation outcomes incorporates this dynamic effect.

Where new low-intensity grassland patches are created next to each other, creating clusters or corridors of enrolled land, this may result in additional ecological benefits if the species in question responds positively to such spatial coordination. A payment for actions scheme does not provide specific incentives for such spatial coordination unless it is supplemented by an agglomeration bonus (e.g. Banerjee et al., 2014, Liu et al., 2019). A payment for outcomes scheme may indirectly encourage such coordination, but only if neighbors can agree to coordinate their management actions. No such coordination between neighbors is modelled in this paper, although this is an interesting focus for future work. We also note that our hybrid scheme and the payment for modelled results scheme approach the idea of employing a perfectly-differentiated payment scheme to achieve the biodiversity target. As shown in Armsworth et al. (2012), such a scheme would incorporate both the variation in ecological productivity across locations (as captured in an ecological model such as that used here), and the variation in opportunity costs across farmers. Our payment for modelled results does the former but not the latter – payments are set on the basis of the marginal supplier, as shown in Fig. 3. This means the budgetary cost of the payment for modelled results scheme will exceed that of a perfectly-differentiated payments for action scheme, if one ignores transactions costs.

Payment for modelled results also does not get around the moral hazard problem of farmers' actions in implementing the contract being hidden/costly to observe, so the regulator still needs to monitor farmer actions which are contracted under the AES policy. This monitoring of actions is also needed, of course, under the standard payment for actions approach, unless some self-enforcing contract design is used. In contrast, under payment for measured or actual outcomes, the regulator does not need to worry about monitoring what actions the farmer takes, since we only care about these measured outcomes, not how they were generated. Finally, a payment for modelled results approach does not address the issue of spatial interdependencies, in the sense that the actual biodiversity outcome on a given farm from following an advised (and contracted) management change may depend on how land on neighboring farms is managed (Sabatier et al., 2012).

Our hybrid approach involves spatially weighting payments for action, and thus realizing some of the gains possible under payment for modelled results (those due to more spatial targeting of restoration actions), without involving a major shift away from current policy design. The variables used to spatially weight payments (distance to urbanization, presence of power lines) are those which come out as important in the ecological model given that our objective is a net gain in lapwings. Whether this way of spatially-weighting payments for our target outcome (lapwings) has beneficial off-market effects (in our case on curlews and oystercatchers) is likely to be context-specific. It depends on species complementarities (the sense in which an action taken to benefit species x also benefits species y), and the spatial correlation between agricultural rents and species distributions. Moreover, If some farms or relevant decision-making units are much larger than our 1 km x 1 km grid squares, then any economic or ecological scale or scope effects at the whole farm scale would not yet be captured. It should also be noted that the payment for actions scheme modelled here relates to discrete changes in land use – away from cropping or grazing to low-intensity grassland – rather than continuous changes in some management variable such as fertilizer application rates or stocking density, which have been used in other payment-for-actions studies in similar settings (eg Armsworth et al., 2012).

A crucial aspect of payment for modelled results is the accuracy of the ecological modelling used to produce predictions of expected outcomes from changes in land management. For our species abundance model, predictions are less reliable for land parcels in areas where data are sparse, and for the few parcels that hold particularly high abundances of birds. Furthermore, our model does not take into account temporal dynamics or spatial spillovers that might exist in terms of agglomeration benefits. However, there is clearly a general issue here in terms of how good a model has to be before it is good enough to be used in a payment for modelled results policy (see, for example, Bunnefeld et al., 2011, albeit in a different environmental management context). We also note that the empirical literature has shown that a multiplicity of factors can determine farmers' decisions about whether or not to participate in agri-environment schemes. These extend far beyond the monetary rewards of joining versus not joining, and include issues such as the length of contract offered, who is responsible for monitoring scheme results, the characteristics of individual farmers, and the perceived behavior of other farmers in an individual's peer group (Dessart, et al., 2019; Murphy et al., 2014; Baumgart-Getz et al., 2012). None of these wider factors are captured in our agent based model, which simply predicts participation on the basis of relative monetary pay-offs alone. We also note that alternative types of bio-economic (ecological-economic) frameworks could be used to investigate the performance of payment for predicted results incentives, rather than the Agent Based Model combined with a Species Abundance Model used here.

Finally, a major challenge when designing results-based AES is the choice of the result indicator (Fleury et al., 2015). This problem attaches to payment for modelled results as well: which indicator that an ecological model is capable of producing will be chosen for use? One can imagine lobbying over the choice, if the nature of the indicator on which payments are based affects the expected payoffs of land managers. Here we use single species indicators, but more complex biodiversity indicators (such as DEFRA's Net Gain indicator in England: Natural England, 2021) may find more favour amongst stakeholders. However, ecologists will want to be assured of the model's capability of producing accurate, stable-over-time and generalizable forecasts, since it is actual biodiversity or environmental quality outcomes that are ultimately relevant for society. This necessitates some expenditure on monitoring actual outcomes, and comparing these to the policy model's predictions (by "policy model" we mean the ecological model used to generate the predictions on which contracts are made). However, determining whether a set of measured outcomes is evidence that the policy model is wrong, and what is wrong with it, is no simple task.

5. Conclusions

This paper undertakes an empirical examination of the relative ecological and economic outcomes of three different designs of agri-environmental policy aimed at increasing the population of an endangered farmland bird, the lapwing. In particular, we are interested to examine the likely consequences of implementing the "payment for modelled results" idea recently suggested by Bartkowski et al. (2021). For a given overall budget, ecological outcomes vary significantly between payment for modelled results and payment for actions, whether the latter is spatially-differentiated or not. We find that payment for modelled results leads to bigger increases in both the target species and off-target farmland waders, even though the area of habitat restored is lower. Economic outcomes also change. Farm surplus is higher under payment for modelled results, even though the numbers of farmers participating is lower.

Because these differences in outcomes relate to specific spatial relationships in observable variables (agricultural profits, land use and predicted bird numbers), our results have broad implications for AES design globally. However, we raise an important question in terms of "how good is good enough?" in terms of the ecological model used to predict the outcomes which form part of the contract design.

CRediT authorship contribution statement

Problem conception: **KS, NH, PA**. Ecological modelling: **KS, MD**. Economic modelling: **KS, NH**. Literature review: **MN**. Paper writing: All named authors..

Declaration of interest

The authors declare no financial interest in the funding or findings of this research.

Data availability

The authors do not have permission to share data.

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