

Linking Agri-Environmental Policy to Species-Level Responses Through GPS Tracking

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Abstract

Under the new Common Agricultural Policy (CAP), it is mandatory to directly evaluate whether measures in member states' Strategic Plans achieve their environmental objectives. Reversing the decline of farmland birds, particularly endangered steppe birds, is one of such goals. Rarity and elusive behaviour often preclude gathering data on the space use and habitat selection of endangered birds, but recent advances in GPS tracking have opened new opportunities. We analyse available tracking data for six species of endangered steppe birds that inhabit farmland across four regions of Spain to compare the use of areas with and without CAP measures applied in 2023 aimed for their conservation (the eco-scheme "Biodiversity Sites" and Rural Development interventions targeting farmland birds). We apply both Before-After-Control-Impact (BACI) designs with pre-measure data and classical same-year selection functions, developing filtering and analytical criteria. We expected a more frequent use of plots with CAP measures both in the same year and after measure application. Our findings show no clear trends and differences between species, with some measures positively influencing habitat selection, while others showed non-significant or even negative effects. Further, there was no consistency between results of classical same-year and BACI models, underscoring the importance of continuous monitoring and multi-year sampling. Although results were still not fully conclusive, our framework and methodology offer a practical approach to assess long-term effects of CAP measures on rare and endangered species, including birds and other species protected by the European Habitat Directive that are suitable for GPS-GSM monitoring.

1. BACKGROUND

Centuries of land management have profoundly shaped Europe's landscapes, from early agricultural practices to traditional land-use systems, resulting in the diverse ecosystems and habitats we observe today (Plieninger et al. 2016; Schulp et al. 2019). Nowadays, agriculture is widely recognized as a major driver of environmental change, with modern land use trends, including agricultural intensification and land abandonment, significantly contributing to biodiversity loss across Europe and globally (Dudley and Alexander 2017; EEA 2020). In this context, addressing the current biodiversity crisis and other global challenges requires conservation strategies that go beyond preserving natural or protected areas and isolated reserves (Green et al. 2005; Mace 2014; Kremen and Merenlender 2018; Díaz 2023) and consider sustainability of agricultural ecosystems, rethinking how food is produced and consumed (Tilman and Clark 2014). Moreover, in the European context, there is strong evidence that low-intensity extensive farming systems are not only compatible with biodiversity but are essential for maintaining it, supporting species communities that have adapted over time to agricultural environments (Sutherland 2004; Batáry et al. 2015; Benedetti 2017; Bugalho et al. 2025).

The Common Agricultural Policy (CAP) is the primary framework determining agriculture in the European Union and receives over one third of the EU's budget (Díaz et al. 2021). While CAP's original aim was to increase agricultural production, its last reform (CAP 2023–2027) places biodiversity, climate action, and resource management at its heart. A main novelty of the 2023–2027 CAP is the Green Architecture,

which brings together three complementary instruments: (i) enhanced conditionality, which ties farm subsidies to compliance with environmental and social legislation; (ii) eco-schemes, aimed at promoting simple and widely applicable practices that benefit biodiversity and climate adaptation; and (iii) Rural Development measures that support more targeted environmental and animal welfare actions tailored to regional priorities (EU CAP Network 2022). Each Member State is responsible for designing its own CAP Strategic Plan to meet these goals, based on the best available scientific evidence and including evaluation of measures' effectiveness.

The conservation of farmland birds has been identified as a key priority in Spain's Strategic Plan (Pérez-Pozuelo et al. 2024), aligning with EU environmental objectives in response to the ongoing decline of farmland bird populations across Europe (see EU's Farmland Bird Index (2025)). These declines reflect a broader biodiversity crisis and highlight the urgent need for effective policy interventions (Tscharntke and Batáry 2023). Steppe birds are especially endangered farmland birds due to strict dependence on open landscapes, ground nesting habits and large body size (Gómez-Catasús et al. 2025). They are one of the most endangered avian groups in Europe (Burfield et al. 2023), with drastic declines in population sizes and ranges primarily due to land-use changes such as agricultural intensification, afforestation, urban and infrastructure expansion, and the abandonment of low-productivity farmland (Gómez-Catasús et al. 2025). Assessing the effectiveness of CAP measures aimed at conserving farmland and steppe birds is crucial not only to address the specific threats facing these species, but also to contribute to the EU's broader biodiversity conservation goals (Pérez-Granados et al. 2025).

Traditional monitoring methods for common farmland birds tend to be insufficient when it comes to rare, elusive, well-camouflaged and highly mobile species, such as endangered steppe birds (Gaget et al. 2019; Ferraz et al. 2024). Moreover, traditional monitoring approaches generally also lack the spatial and temporal resolution needed to detect fine-scale habitat selection, a limitation increasingly highlighted when compared with high-precision GPS telemetry datasets (Kays et al. 2015). However, recent advancements in GPS-GSM and satellite tracking have markedly enhanced our capacity to study these species: the miniaturization of tracking devices, making them smaller and lighter has enabled their use on an increasing range of species, allowing for precise, real-time monitoring that provides valuable insights into animal movement, behaviour and habitat use (Cagnacci et al. 2010; López-López 2016; Tarjuelo et al. 2020; Sanz-Pérez et al. 2022; Revilla-Martín et al. 2026). These technologies have proven useful for identifying critical habitats and understanding human impacts on wildlife, ultimately allowing for more effective conservation strategies (Hebblewhite and Haydon 2010). Moreover, the integration of collaborative monitoring networks can amplify the benefits of telemetry by extending spatial coverage, reducing operational costs, and improving data collection efforts (Urbano et al. 2021). Supported by international funding initiatives aimed at conserving threatened species (CBD 2022), GPS-GSM telemetry serves as a tool for complementing the evaluation of the effectiveness of conservation measures on these endangered species.

This study integrates GPS-GSM tracking data from endangered steppe birds with spatial information on CAP-funded conservation measures, implemented at the field level, targeting the declining trends of

farmland birds, as defined under Need 06.02 of the Spanish Strategic Plan (Appendix S1: Section 1 ; see (Pérez-Pozuelo et al. 2024) for a full description of measures). We evaluate whether fields with conservation measures were selected by steppe birds as compared to those without such measures, expecting a positive influence of these interventions on habitat selection. Besides classical selection functions analysing habitat selection patterns in the year when measures were first applied (2023), we also developed Before-After-Control-Impact (BACI) designs using data of both 2023 and the previous year (2022), where possible. Apart from analysing whether fields under CAP-funded measures were positively selected by steppe birds, we also developed an explicit analytical framework for the analyses of GPS-GSM data of species linked to agricultural habitats, providing the corresponding R scripts that could be applied to other endangered species.

2. METHODS

2.1. Study area and species

The research was conducted across several regions of Spain, within the autonomous communities (Spanish administrative regions) of Cataluña, Castilla y León, Castilla-La Mancha, Andalucía and Extremadura (Fig. 1). These areas were chosen based on (1) the availability of GPS-GSM tracked bird data; (2) their importance for steppe bird conservation (Medrano-Vizcaíno et al. 2025); and (3) the application of measures of Spain's Strategic Plan for the Common Agricultural Policy (PEPAC) aimed at the conservation of farmland birds (González-Pulido et al. 2026).

2.2. Tracking data, CAP measure application and land uses

Study species were stone curlew *Burhinus oedichnemus*, Montagu's harrier *Circus pygargus*, lesser kestrel *Falco naumanni*, pin-tailed sandgrouse *Pterocles alchata*, black-bellied sandgrouse *Pterocles orientalis* and little bustard *Tetrax tetrax*. All are strongly declining both in Spain and elsewhere in Europe and are thus included in both red and official lists of endangered bird species (Gómez-Catasús et al. 2025). Bird data were gathered by specialist researchers who are part of the Steppe Bird Research Group GIAE (<https://giaesteparias.org/>). Tracking data were collected using different GPS-GSM telemetry devices and dataloggers from Druid (<https://druid.tech/>) and Ornitela (<https://www.ornitela.com/>), with the specific model and transmitter weight adjusted for each species to ensure compliance with the maximum allowable load for animal welfare. These devices provided location data during 2022 and 2023 with spatial resolutions of approximately 30 m and 5 m depending on the model (Ferraz et al. 2024). Two datasets were compiled: one containing only 2023 data, and another combining data from both 2022 and 2023, to allow for before-after comparisons of habitat use in relation to the implementation of CAP measures. Data selection and filtering processes ensured temporal and spatial consistency across both datasets (see below).

The application of CAP measures aimed at the protection of farmland birds was provided as a map with information at the field scale by the Spanish Ministry of Agriculture, through a collaborative agreement

with the Spanish National Research Council (CSIC). These measures, part of the 2023–2027 CAP framework, began to be implemented in 2023. The interventions analysed included the eco-scheme “Biodiversity Sites”, which involves the establishment of areas dedicated to protecting natural resources and supporting biodiversity conservation (refuge and food resources for birds, insects, pollinators, and other wildlife) on arable land and permanent crops; and the Rural Development measures “Birds Protection”, which comprises a set of actions aimed at maintaining and/or improving habitat conditions for bird communities, and “Sustainable Crops”, which focuses on the maintenance or restoration of specific crop types considered more beneficial for soil health, biodiversity, and the environment. Appendix S1: Section 1 provides detailed names of the specific measures and their corresponding administrative codes by region. Land use information for each plot was obtained from the 2023 Spanish Agricultural Plots Information System application (SIGPAC), accessed through publicly available online databases maintained by each Autonomous Community (Generalitat de Catalunya 2023; Junta de Andalucía 2023; Junta de Castilla-La Mancha 2023; Junta de Castilla y León 2023; Junta de Extremadura 2023)

2.3. Pre-processing and processing GPS-GSM data

Datasets containing GPS-GSM tracking data were pre-processed to ensure spatial and temporal consistency across individuals and years. For each individual, only one location per hour was retained, after excluding in-flight positions and spatial outliers (see Appendix S1: Section 2 for specific filtering criteria for each species).

We selected the months with data for all individuals of each species, and before-after comparisons were restricted for periods with data for both years (see Appendix S3 for details). Time periods during which birds were moving between areas were excluded from the analysis, with a focus on the breeding season and the pre- and post-breeding periods, when individuals typically exhibit more stationary behaviour. For the little bustard, period selection was conducted at the individual level rather than at the species level (Appendix S1: Section 3), due to its more variable movement patterns (pre- and post-reproductive movements) that differ between individuals and regions (García de la Morena et al. 2015; Coutinho Soares et al. 2025; González del Portillo et al. 2025), with analyses focusing on periods when individuals remained stationary.

2.4. Home range estimation, random point generation, and spatial integration of land use and agricultural measures

Home ranges were estimated using Kernel Density Estimation (KDE) at the 99% isopleth, performed with the kernelUD function from the adehabitatHR v0.4.22 (Calenge 2011). The KDE was calculated separately for each individual, using the href method for bandwidth selection, a grid size of 100 x 100 meters, and the default extent. The calculation of the kernels was done separately for the 2023 dataset and for the combined BACI dataset (2022–2023). For the latter, independent kernels were calculated for each individual and year. Only GPS locations (hereafter presence points) within these estimated home ranges were used in subsequent analyses. Within each home range, 10 random points were generated

for each presence point inside the home range to estimate habitat availability (ratio 1:10). A higher number of random points reduces sampling variance, enhances coefficient estimate stability, and mitigates Monte Carlo error in logistic regression models, but increases computational demands (Fieberg et al. 2021). Spatial data processing in R was carried out using the packages *sp* v2.2-0 (Pebesma and Bivand 2005), *sf* v1.0-21 (Pebesma 2018), and *dplyr* v1.1.4 (Wickham et al. 2014).

Land use categories from SIGPAC 2023 (Appendix S1: Section 4) were reclassified into the eight main Spanish agricultural systems defined by (2021) and (2024): Agrosilvopastoral (PA, PR); Extensive grazing (PS); Fruit orchards (OP, CF, CS, CI, CV, FF, FL, FS, FV, FY); Arable land, including rice paddies (TA, TH); Olive groves (OC, OV, OF); Vineyards (VF, VI, VO); and Others (rest of categories not mentioned before). The Mixed Eurosiberian category was not represented in the study. Before integration, the spatial layers of CAP measure application provided by the Ministry of Agriculture were corrected for topological and geometric errors (Clemente-Orta et al. 2025). Next, information on CAP measure uptake and land use was spatially joined to both presence points and the set of random points generated within home ranges. Spatial processing was conducted using QGIS version 3.34.10. In addition, descriptive metrics were derived by calculating the proportion of each CAP measure within the 99% KDE home range and the 50% KDE core area of the analysed individuals.

2.5. Selection functions, BACI designs and comparison among modelling approaches

We applied logistic mixed-effects models to evaluate the influence of CAP measures on species presence. The binary response variable (presence point = 1, random point = 0) was modelled using two approaches.

First, classical selection functions (Manly et al. 2002) were used to test the effect of CAP measures on plot selection during 2023 only. Individual identity, nested within the Autonomous Community, was included as a random effect to account for regional variation among Autonomous Communities and for differences among individuals within each community. Land use was included as a fixed effect to account for selection based on habitat types. Species-specific models were developed for each measure ("Biodiversity Sites", "Birds Protection" and "Sustainable Crops"), with measure status included as a binary predictor indicating whether the plot was subject to the corresponding measure. The interaction between land use and measure status was not included because it prevented model convergence. The model structure for 2023 was: $\text{Presence} \sim \text{land use} + \text{measure status} + (1 \mid \text{Autonomous Community} / \text{Individual ID})$.

Secondly, the BACI models included an interaction between treatment status and year (2022 vs. 2023). Treatment status indicates whether a plot received CAP measures in 2023 (treated) or remained untreated (control). For the BACI analyses, plots designated as treated in 2023 are coded as to be treated in 2022, allowing for the assessment of temporal changes in species presence attributable to the implementation of CAP measures. Consequently, the interaction between treatment status and year quantifies the effect of treatment while controlling for baseline differences between plots. Random

effects structure and inclusion of land use as a fixed effect were maintained. The model structure for the BACI models was $\text{Presence} \sim \text{land use} + \text{measure status} * \text{year} + (1 | \text{Autonomous Community} / \text{Individual ID})$. Weights were incorporated into the models, with a value of 1 for presence points and 1000 for random points to approximate an inhomogeneous Poisson point process (Fithian and Hastie 2013; Fieberg et al. 2021). For the BACI models, the number of presence and random points was equalized across years by randomly subsampling, ensuring identical sample sizes for each category in 2022 and 2023. Species-specific models were developed for each of the three evaluated CAP measures, using individuals tracked during the analysed periods (2023 only or combined BACI datasets). Some species-measure combinations were excluded due to the absence of individuals in treated plots. For the analyses of the “Birds Protection” measures, individuals from Andalucía were excluded because no uptake of this measure was recorded in 2023 in this autonomous community under the 2023–2027 CAP.

Comparisons between results obtained from the 2023-only selection functions and the BACI designs were conducted by evaluating the effect sizes of the fixed factors using a General Linear Model. Effect sizes were used instead of raw parameter estimates to account for heterogeneity in sample sizes between the 2023 and BACI analyses (Wilson 2023). Effect sizes were calculated from the probability of type I error of parameter estimates, computed from parameter values and their standard errors assuming they follow a Student’s *t* distribution, and sample sizes, following Wilson (2023). For the 2023 models, effect sizes were derived from the evaluated CAP measure, whereas for the BACI models they were obtained from the treatment × year interaction term. Effect sizes from the BACI models were used as the dependent variable, effect sizes from the selection function models as the fixed factor, and the three evaluated CAP measures and the six species were included as random effects.

Additional analyses were conducted for species with sufficient sample sizes to assess whether the effects of CAP measures differed among autonomous communities. Separate models were fitted when at least 10 tracked individuals were available within each autonomous community.

All models were fitted using R version 4.3.1 (R Core Team 2025) with the RStudio interface (Posit team 2025). We used *glmmTMB* v1.1.13 and *lme4* v1.1-37 (Bates et al. 2015; Brooks et al. 2017) for model fitting, and absence of collinearity among predictors was assessed using the performance package v0.15.2 (Lüdtke et al. 2021).

3. RESULTS

Individual tracking data were concentrated from April to June (breeding periods, when individuals tend to show a more stationary behaviour), with additional data from the early breeding period for lesser kestrels and from post-breeding periods in July-September for lesser kestrels and stone curlews (Table 1A; see Appendix S1: Section 3 for the exact periods selected for each individual bird). The number of tracked individuals analysed per species and Autonomous Community varied between one (e.g. stone curlews in Castilla-La Mancha or Montagu’s harriers in Extremadura) and 12 (stone curlews during breeding in Extremadura) (Table 1B).

Table 1. Sampling period of GPS-GSM tracking data and number of monitored individuals per species and Autonomous Community included in the analyses for each steppe bird species. A. Period: Months highlighted in green represent those analysed in the 2023-only dataset, while months included in the BACI analyses are indicated with an “X”. **B. Location:** Sample sizes in brackets indicate the number of individuals included in the BACI analyses, while those without brackets correspond to individuals analysed for the 2023-only dataset. BO = *Burhinus oedicephalus*, CP = *Circus pygargus*, FN = *Falco naumanni*, PA = *Pterocles alchata*, PO = *Pterocles orientalis*, TT1 = *Tetrax tetrax* period 1, TT2 = *Tetrax tetrax* period 2, AND = Andalucía, CAT = Cataluña, CYL = Castilla y León, CLM = Castilla-La Mancha and EXT = Extremadura.

	A. Month												B. Location and sample sizes					
	J	F	M	A	M	J	J	A	S	O	N	D	AND	CAT	CLM	CYL	EXT	Total
BO				X	X	X	X							10 (4)	1		12 (3)	23 (7)
CP				X	X	X							3 (1)				1	4 (1)
FN													6					6
PA				X	X									4	4 (1)		4 (2)	12 (3)
PO				X	X										4 (3)		4 (3)	8 (6)
TT1				X	X	X							1 (1)	8 (3)		4 (1)	11 (6)	24 (11)
TT2							X	X	X				1	7 (6)	1	6 (2)	9 (5)	24 (13)

In 2023, the “Biodiversity Sites” measure showed positive effects on field selection by stone curlews, sandgrouse and little bustards, while negative effects were observed for Montagu's harriers and lesser kestrels, but when analysing the combined BACI data, pin-tailed sandgrouse showed negative effects and Montagu's harriers positive ones (Fig. 2). The “Birds Protection” measure had positive effects on field selection by little bustards in the BACI analysis, but negative effects on all other species. However, considering only 2023 data, it had positive effects on field selection by stone curlews and pin-tailed sandgrouse (Fig. 2). The “Sustainable Crops” measure showed negative effects for little bustards during the first period in both analyses. In contrast, it had positive effects in the BACI analysis for little bustards in the second period and for Montagu’s harriers, although the 2023-only analysis revealed negative effects (Fig. 3). Detailed model outputs are provided in Appendix S2.

Overall, the proportion of each CAP measure within both the 99% KDE and the 50% KDE core area was very low, with no species exceeding 21% for the “Biodiversity Sites” measure or 15% for any Rural Development measure, based on averages across all individuals of each species (Appendix S2: Section 1). In addition, regional analyses indicate that the effects of CAP measures may differ between autonomous communities (see Appendix S2: Section 2: Table 2).

The model assessing the similarity and consistency between the effect sizes of the 2023-only models and the combined BACI models, including random effects to account for variability between species and measures, showed no significant effects (Estimate = -0.25, $p > 0.1$). Spearman rank correlation also indicated no significant association (Spearman's rho = -0.28, $p > 0.1$).

4. DISCUSSION

4.1. Ecological effectiveness of CAP measures

The availability of fine-scale data on animal locations and field-level implementation of conservation-oriented CAP measures was successful in assessing whether fields under specific interventions were positively selected by endangered steppe birds, providing a first evaluation of its ecological effectiveness for rare and endangered species. Overall, the three CAP measures showed heterogeneous effects across species. In the BACI analysis, “Biodiversity Sites” showed positive effects on field selection by black-bellied sandgrouse, but negative effects on pin-tailed sandgrouse and stone curlew and inconsistent effects on little bustards depending on the period. “Birds Protection” was mostly negative, with positive effects only for little bustards in one of the analysed periods. “Sustainable Crops”, in turn, had positive effects on Montagu’s harriers and stone curlew, and on little bustards in the later period, while early effects on little bustards were negative. Importantly, the very low spatial coverage of these measures within home ranges suggests that their ecological influence may currently be constrained, potentially limiting their capacity to generate measurable individual-level benefits. Scant consistent effects showed both positive and negative selection of fields with measures, but with no clear pattern. Further studies will be needed to shed light on the biological drivers underlying consistency or lack thereof.

4.2. Importance of BACI designs and multi-year approaches

BACI designs, including data from both before and after measure implementation, provide a clearer assessment of how interventions influence habitat selection, but are also much more difficult to achieve, hence sample size was much more limited for this type of analysis (Table 1). While some species showed increased selection of plots with measures in 2023, these patterns often did not persist when compared with their distributions in 2022. Comparing effect sizes from the 2023-only and BACI analyses revealed inconsistent effects across species. Results from the 2023-only analyses failed to reliably predict those from the BACI analyses, suggesting that the 2023 patterns alone may not reflect true effects of the measures. Small sample sizes highlight however the need for more multi-year, before-and-after designs for drawing reliable conclusions about the true effects of conservation measures and for detecting genuine conservation impacts (De Palma et al. 2018).

The analysis is primarily focused on the first year of CAP 2023–2027 measure implementation, which may have been affected by transitional limitations, including administrative delays, low farmer engagement (Carricondo et al. 2012; Iglesias et al. 2012), and relaxation of measures due to exceptional circumstances, such as a severe drought and broader economic and geopolitical impacts of the war in Ukraine (Morales et al. 2022). In this context, the uptake of CAP measures was very low in the areas analysed, suggesting limitations in their ecological effectiveness. From an analytical perspective, however, low uptake may have minimized potential dilution effects. Furthermore, as this study focuses

exclusively on measures introduced in 2023 within the CAP 2023–2027 regulatory framework, it does not consider multi-year commitments from prior CAP periods that may still be in effect. Additionally, we did not have information on whether parcels newly enrolled in 2023 had been subject to similar measures under earlier CAP frameworks. These factors illustrate both the vulnerability of conservation policies to short-term implementation constraints and the critical need for multi-year evaluation methodologies. Longitudinal monitoring enables the tracking of fields where measures are sustained, captures delayed or cumulative ecological responses and provides a more complete understanding of the effectiveness of conservation measures over the entire implementation period.

4.3. Advantages and future challenges of BACI designs with GPS-GSM tracking data

High-resolution GPS-GSM tracking provides a precise scalable monitoring, allowing for fine-scale, individual-level tracking of habitat selection and behavioural responses over time (Fiedler 2009; Revilla-Martín et al. 2026). This method represents a valuable alternative to conventional censuses, particularly relevant for elusive or wide-ranging species (Gaget et al. 2019; Ferraz et al. 2024), which are difficult to monitor at the spatial scale of CAP measures using traditional approaches.

In this study, we relied on a pre-existing high-resolution GPS-GSM dataset that was not originally designed to evaluate CAP measures. Consequently, the study design was constrained by small sample sizes for certain species and regions, and it was not possible to assess measures separately by Autonomous Community, which vary under the Rural Development Plan, and effects may differ regionally (see Annex 5). Additionally, the analysis was limited to periods when sufficient GPS-GSM tagged bird data were available, focusing on times when birds were more stationary to allow the calculation of individual home-range areas. These challenges could be easily addressed by establishing GPS-GSM bird sampling specifically designed to assess the effects of CAP measures on these species, which would ensure adequate sample sizes in areas of interest based on the implementation of measures or land uses.

The high costs associated with tagging and the sustained effort required to maintain adequate sample sizes (due to individual mortality and changes in home ranges over time, and limited duration of GPS-GSM devices in smaller species) pose significant challenges to the systematic application of BACI designs across all species and territories. While GPS-GSM tracking is not meant to replace traditional methods like censuses and systematic mapping, which provide valuable population-level information at local scales, it offers a valuable approach for long-term, fine-scale evaluation of conservation policy effects on certain rare species. Furthermore, while we focused on periods of higher site fidelity to facilitate home-range delineation due to dataset limitations, GPS-GSM tracking offers the potential for monitoring space use throughout the entire annual cycle. Developing alternative criteria for defining use areas (e.g., 80% or 50% kernel densities, or other functions like Brownian bridge estimators for migration periods, see González del Portillo et al. (2025)) could allow for the evaluation of measure effects beyond the breeding period.

4.4. From field selection to demography benefits

The primary objective of this study was to assess whether birds select or avoid fields with specific CAP measures. However, a key challenge is determining whether this selection of plots with measures corresponds to genuine demographic benefits (e.g. improved reproduction or survival) or simply attraction to treated plots. Recent evidence from the little bustard illustrates this issue, showing that while fallow management can improve breeding success, it may not be enough for full population recovery (Mañosa and Bota 2023).

Additionally, while this study focuses on field-scale factors, the conservation of steppe bird populations is also shaped by broader landscape-level variables. Previous research has shown that the success of agri-environmental schemes depends not only on field management but also on the surrounding landscape context, particularly habitat heterogeneity, the extent of semi-natural vegetation, and connectivity (Concepción et al. 2008, 2012; Díaz and Concepción 2016). Although some CAP interventions, such as “Biodiversity Sites”, aim to enhance these features, current targets (e.g. 3–7% non-productive elements, MAPA, 2023) are likely insufficient to meet the ecological requirements of many farmland birds (Pe’er et al. 2019; Díaz et al. 2021), and should also be addressed to ensure real conservation outputs.

Our two-year dataset provides an initial perspective on the effectiveness of these measures and should be complemented by longer time series and the integration of GPS-GSM tracking with demographic data (e.g., breeding success or survival rates) to evaluate whether field-level gains translate into broader population outcomes. This will help link local-scale responses to regional or national conservation targets (Kleijn et al. 2011).

4.5. Methodological considerations

We developed specific processing strategies to handle CAP measures, land use data, and GPS-GSM data. These strategies were designed to mitigate the potential effects of bird dispersal or migratory movements on defining home ranges and accurately identifying non-selected locations. Additionally, we integrated environmental data and uptake information, creating scripts to generate random points within these areas and perform the corresponding analyses. These processing and analytical procedures were implemented in R scripts (Appendix 3) that can be applied to analyse GPS-GSM tracking data from other species. GPS-GSM devices have typically been deployed on large-bodied species due to transmitter size and battery constraints, although ongoing miniaturization is expanding the range of species studied (Cagnacci et al. 2010; Tomkiewicz et al. 2010). Because large body size is associated with lower population densities and a higher extinction risk in birds and mammals (Cardillo et al. 2005; Chichorro et al. 2022), this methodology is particularly relevant for species of conservation concern.

Scripts can be adapted for other species by modifying the sections corresponding to species-specific filtering and processing. Parts 1 and 2 of the code devoted to pre-processing should be adjusted to reflect the biological and behavioural characteristics of the focal species. In this study, which focuses on

birds, these sections include filtering outliers, removing flying points when necessary, and selecting specific months of interest. For other taxa, equivalent filtering criteria (e.g., movement thresholds, habitat constraints, seasonal periods) should be defined accordingly. Similarly, in Part 3, kernel density estimation parameters (e.g., bandwidth selection and the calculation of core areas or 99% kernel home ranges) may require adjustment depending on species ecology, movement patterns, and study objectives. By implementing these species-specific modifications, the analytical framework can be consistently applied to a wide range of species tracked using GPS-GSM technology.

5. CONCLUSIONS

This study represents an initial step towards directly evaluating the ecological effectiveness of biodiversity-focused CAP measures for endangered steppe birds. While some encouraging associations between measures and species' habitat selection were found, results were inconsistent and often failed to hold when considering prior distributions. This underscores the need for cautious interpretation of short-term presence data and highlights the importance of long-term, ecologically grounded monitoring.

The methodology developed here offers a framework for monitoring species difficult to assess with traditional census methods and which helps overcome the limitations of these methods to obtain high-quality, high-resolution information on species' responses to specific measures, serving as an initial approach to evaluate the effects of CAP measures on these species. It can also be applied to other species with available tracking data, thereby enhancing its utility in assessing the effectiveness of conservation interventions across diverse taxonomic groups.

Our study goes beyond evaluating the content and stated objectives of CAP measures or focusing solely on assessing compliance and spatial allocation. It represents a feasible approach to evaluate the actual ecological effectiveness of PEPAC measures on endangered steppe birds. The future success of CAP biodiversity measures, such as those evaluated here, depends on widespread uptake, appropriate landscape integration, ecological ambition, and robust multi-year adaptive monitoring (Díaz et al. 2021). Without these elements, even well-targeted measures may fall short of reversing the decline of vulnerable species. In order to achieve its conservation goals and align with global and EU biodiversity commitments (Pérez-Granados et al. 2025), the CAP must prioritize measurable ecological outcomes, such as the individual-level use of plots where measures have been adopted, as assessed in this study.

Declarations

Author contributions

Laura González-Pulido: Formal analysis, Methodology, Writing - Original Draft; **David González del Portillo** and **Lara Moreno-Zarate:** Formal analysis, Writing - Review & Editing; **Gerard Bota**, **Gemma Clemente-Orta**, **Eladio L. García de la Morena**, **David Giralt**, **Ana T. Marques**, **Carlos A. Martín**, **Manuel B. Morales**, **François Mougeot** and **Joao P. Silva:** Investigation, Writing - Review & Editing; **Mario Díaz:**

Conceptualization, Methodology, Writing - Review & Editing. All authors contributed critically to the drafts and gave final approval for publication.

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Conflict of interest statement

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.

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Figures

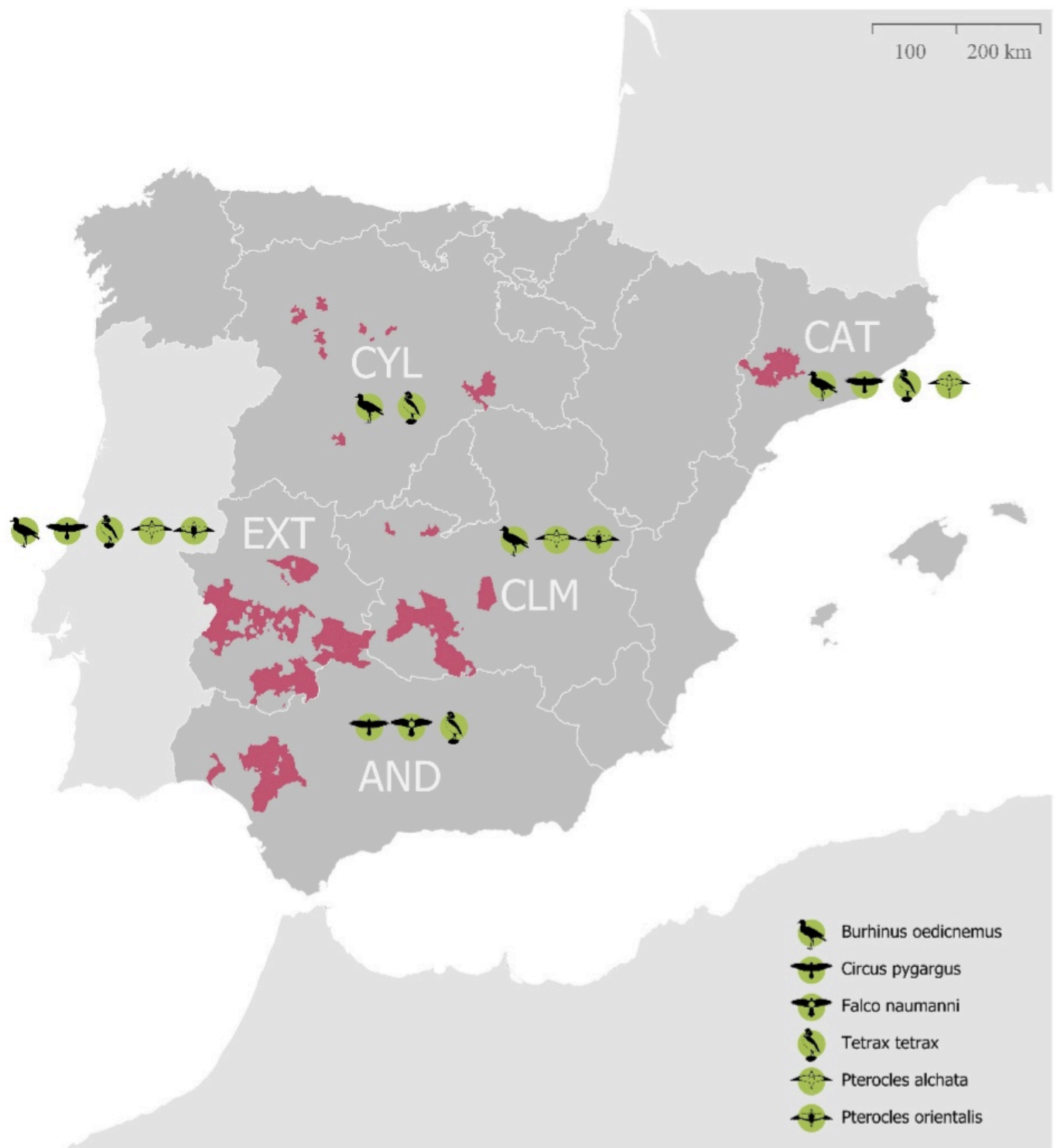


Figure 1

Study areas in Andalucía (AND), Cataluña (CAT), Castilla y León (CYL), Castilla-La Mancha (CLM) and Extremadura (EXT). Boundaries of Autonomous Communities are outlined, and areas encompassing municipalities with presence of GPS-GSM data from at least one individual of the target steppe bird species are highlighted in magenta.

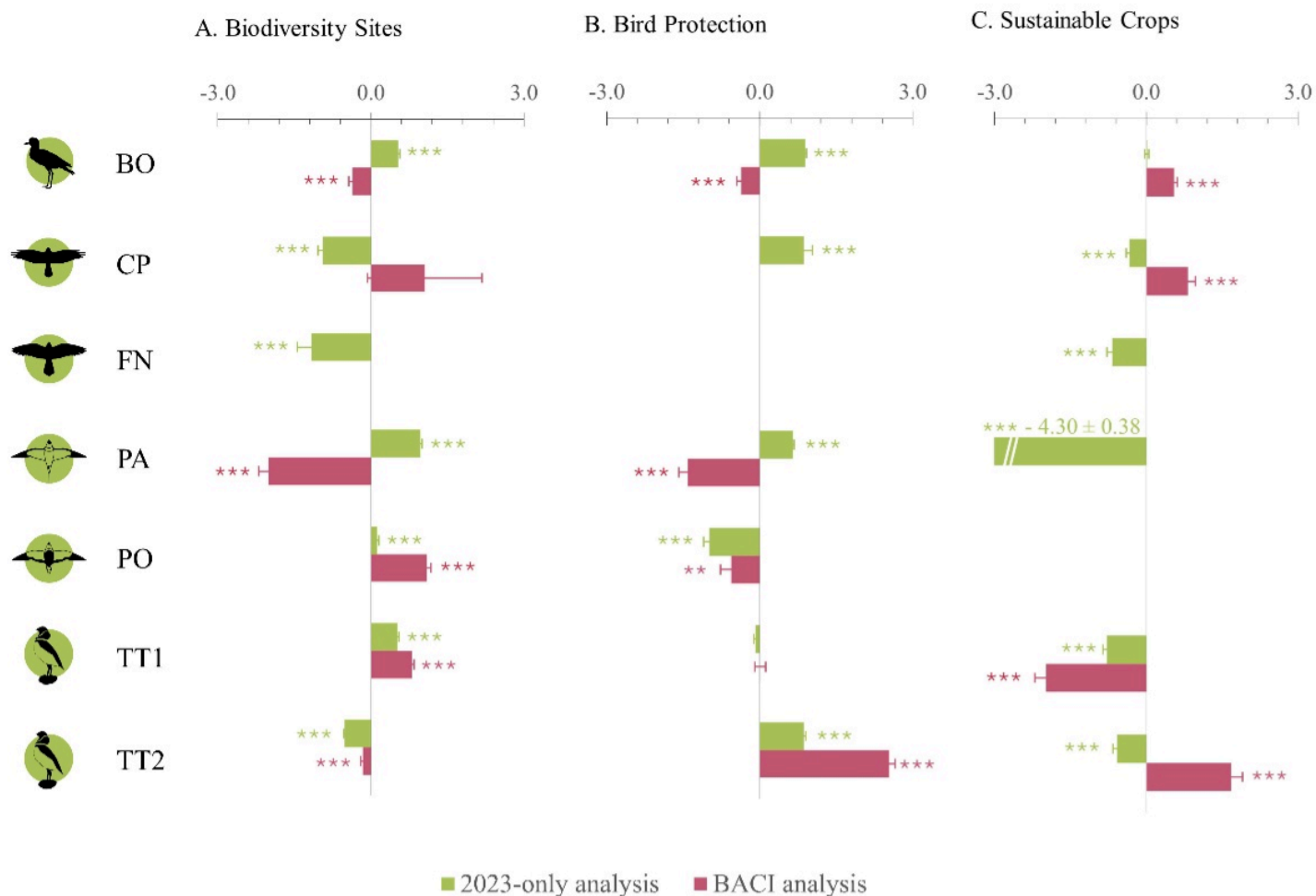


Figure 2

Estimates derived from the fitted logistic mixed-effects models for each species and measure. For models based on the 2023-only dataset, estimates represent the effects of CAP measures on species presence, whereas for the BACI dataset, estimates correspond to the interaction between the analysed CAP measures and year. Error bars represent standard errors, and significance levels are indicated using asterisks: * = p < 0.05, ** = p < 0.01, *** = p < 0.001. BO = *Burhinus oedicephalus*, CP = *Circus pygargus*, FN = *Falco naumanni*, PA = *Pterocles alchata*, PO = *Pterocles orientalis*, TT1 = *Tetrax tetrax* period 1, TT2 = *Tetrax tetrax* period 2.

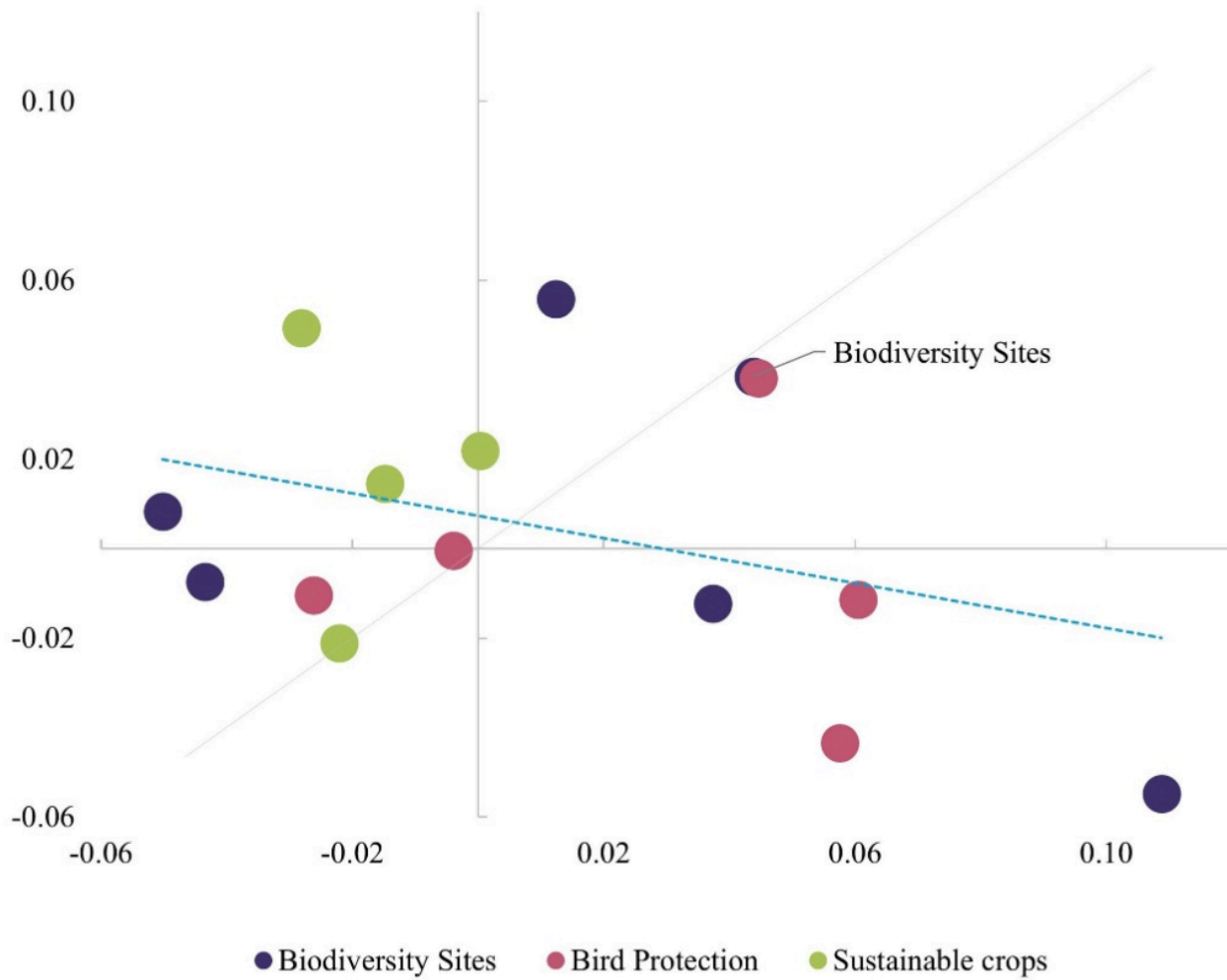


Figure 3

Relationship between effect size estimates from 2023 models and combined BACI models. The x-axis shows values from models developed exclusively with 2023 data, and the y-axis shows values from models based on the combined BACI dataset. The blue dotted line represents the fitted relationship, and the grey line indicates the expected relationship under perfect correlation.