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Research article

Is greening enough? Short-term limited effects of 2015-2022 European Common Agricultural Policy reform on bird diversity in northern Italy

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ABSTRACT

Agricultural intensification is among the major drivers of biodiversity loss, with cascading effects that compromise the supply of essential ecosystem services. To counteract this process, the European Union integrated voluntary agri-environmental measures into the Common Agricultural Policy (CAP). Since 2015, all CAP direct payments have been tied to the adoption of greening measures (crop diversification, permanent grassland maintenance, ecological focus areas). Using birds as reference taxon, we analyzed whether the implementation of both greening and agri-environmental measures, fostered during the 2015-2022 CAP programming period, enhanced the species richness of overall community, farmland specialists, granivores and insectivores. Applying a cross-sectional approach, we first estimated the overall associations between species richness metrics and sustainable management practices (crop diversification, natural element maintenance, organic, integrated, conservation-tillage farming). Then, employing a longitudinal approach, we evaluated if the implementation of greening practices, promoted by the 2015 CAP reform, increased species richness. All metrics were positively associated with crop diversification. Both overall community richness and insectivorous richness were positively associated with natural elements, while the richness of farmland specialists and granivores showed negative responses. Organic and integrated farming generally promoted species richness, while conservation-tillage farming was negatively associated with insectivorous richness. The longitudinal analysis confirmed that overall community richness benefited from greening interventions promoted by 2015 CAP reform, while farmland specialists, granivorous and insectivorous species richness were not affected in the first years following implementation. We call for evidence-based revisions of CAP agri-environmental measures to improve environmental sustainability of farming without undermining socio-economic sustainability.

1. Introduction

Agricultural intensification and the landscape homogenization that it causes are among the greatest threats for biodiversity, causing massive population declines across several taxa (Donald et al., 2001; Millard et al., 2021; Williams et al., 2021). The loss of biodiversity compromises the supply of crucial ecosystem services, such as pest control and pollination, which can ultimately impair agricultural production and human well-being (Frank, 2024; Lippert et al., 2021). Given the inextricable link between biodiversity and agroecosystem management, it becomes essential to develop crop production strategies that simultaneously foster biodiversity conservation and sustain food supply (Rader et al., 2024).

In Europe, this challenge has been addressed through the implementation of agri-environmental measures, which promote extensive agricultural practices to enhance both biodiversity and ecosystem services while compensating farmers for the additional costs of such practices (Boinot et al., 2024; Couthouis et al., 2023; de la Cruz et al., 2023). For example, less intensive land management practices (e.g., organic, integrated, and conservation-tillage farming) benefit multiple

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taxa due to reduced agrochemical inputs and/or decreased soil disturbance (Boeraeve et al., 2022; Filippi-Codaccioni et al., 2009; Moreau et al., 2022; Tuck et al., 2014). Alongside, crop diversification and the maintenance/implementation of natural elements within agro-ecosystems (e.g., hedgerows, woody patches, and wetlands) is another cornerstone of biodiversity-friendly farming practices (Dainese et al., 2017). Indeed, heterogeneous agroecosystems offer suitable habitats and resources for a wider range of species, while increasing ecological connectivity at the landscape scale (Dalpasso et al., 2026; Priyadarshana et al., 2024). Despite these extensive agricultural practices can lower agronomic performances (Seufert et al., 2012), several studies showed that it is possible to implement sustainable agricultural practices without compromising, and in some cases even enhancing, crop yields (Kremen and Merenlender, 2018; Wurz et al., 2022).

To reduce the impact of intensive agriculture on biodiversity, since 1992 the European Union introduced voluntary agri-environmental measures into the Common Agricultural Policy (CAP). After 1999, agri-environmental measures were included within the framework of the EU Rural Development Programs (RDP), namely CAP Pillar II. Pillar II focuses on enhancing the environmental and economic sustainability of rural areas, offering payments for voluntary environmentally friendly farming practices (such as organic, integrated and conservation-tillage farming) to compensate for yield and income losses incurred by adopting farmers. In this context, organic farming regulations mandate crop rotation while banning the use of synthetic agrochemicals and fertilizers, whereas integrated farming restricts their application and amount, and conservation-tillage farming aims to minimize soil disturbance through minimum or no tillage practices. The agri-environmental measures envisaged by Pillar II have been adopted by a limited number of EU farmers, both for CAP budget constraints and for the additional commitments required (Bertoni et al., 2011). However, most of the CAP budget is devoted to Pillar I, that includes direct payments to support farmers' income. To ensure that a greater number of EU farms improve their environmental sustainability, during the 2015-2022 CAP programming period direct payments for all farmers have been conditioned to the compliance with some "agricultural practices beneficial for the climate and the environment" (Regulation (EU) No 1307/2013), otherwise known as greening practices. These were: (1) farm-scale arable crops diversification, (2) permanent grassland maintenance, and (3) a minimum share of arable land devoted to ecological focus areas (woody patches, hedgerows, fallow lands). Under the current CAP (2023-2027), all direct payments for farmers are tied up to their compliance with environmental conditionality basic standards (Regulation (EU) 2021/2115). Since some greening measures introduced with CAP 2015-2022 have been reproposed for the current programming period (e.g., crop diversification is part of 2023-2027 conditionality basic standards), it is crucial to evaluate their effectiveness in promoting biodiversity while ensuring crop production and economic sustainability.

Among animals, birds suffered heavy declines due to agricultural intensification (Rigal et al., 2023; Rosenberg et al., 2019). Still, sustainable agricultural practices can positively affect bird communities (Brambilla and Gatti, 2022; Hološková et al., 2025), potentially enhancing pest control and seed dispersal services (García et al., 2021; Granata et al., 2025). Birds are also good surrogates for overall biodiversity, and their conservation can benefit several other taxa living in agroecosystems (Dalpasso et al., 2025; Sauberer et al., 2004). Thus, understanding how agricultural practices promote bird diversity is important for both biodiversity conservation and the provisioning of ecosystem services (Assandri et al., 2018; Granata et al., 2025). Although studies have analyzed the effects of CAP agri-environmental reforms on birds, most of them have been limited to farmland specialists (Buschmann et al., 2023; Chiron et al., 2013; Ekroos et al., 2019; Josefsson et al., 2017; Šumrada et al., 2021). Yet, considering multiple ecological and functional groups would be highly relevant, as they can exhibit divergent responses to CAP-driven environmental and crop management changes (Chort et al., 2024), leading to different outcomes in terms of ecosystem services.

Leveraging on the availability of thorough monitoring programs of breeding birds in intensively farmed agroecosystems of northern Italy (Lombardy region), we investigated to what extent the implementation of CAP greening practices and voluntary agri-environmental measures affected the species richness of four groups of avian species defined according to different ecological and functional traits, namely overall community, farmland specialists, granivores and insectivores.

We expected that:

- Crop diversification and the maintenance of natural elements would positively affect bird species richness due to increasing habitat heterogeneity and connectivity (Kremen and Merenlender, 2018).
- Organic, integrated and conservation-tillage farming would have positive effects on avian species richness due to the lack (organic) or lower (integrated) use of synthetic agrochemicals or minimized soil disturbance (conservation-tillage), which should increase prey and/or microhabitat availability (Filippi-Codaccioni et al., 2009; Genghini et al., 2006).
- The strength of the effects of these practices on bird richness would differ depending on the ecological and functional traits of species (Chort et al., 2024).

To this end, we first applied a cross-sectional approach (used to analyze general spatial patterns in data), to assess the overall relationship between several sustainable farming practices overlapping with both CAP pillars – such as organic, integrated and conservation-tillage farming, crop diversification, and the maintenance of natural elements – and bird diversity metrics. Then, relying on repeated (farm-level) bird monitoring data, we used a longitudinal approach (used to analyze temporal changes in diversity metrics) to investigate if the implementation of greening practices, promoted by the 2015 CAP reform, affected species richness.

2. Materials and methods

2.1. Study area

The study area encompassed all the lowland and hilly agricultural areas of Lombardy (northern Italy; Fig. 1), the most important Italian region for agricultural production (Falcucci et al., 2007). Lombardy is characterized by intensive farming, dominated by livestock (dairy cattle and pigs) and maize cultivation. Still, maize coexists with several other crops, some of them concentrated in specific areas of the region, like rice and vegetables (Ferrazzi et al., 2017). Because of these characteristics, Lombardy was highly influenced by the 2015 CAP reform, which brought an increase in crop diversification aimed at reducing maize monoculture in favor of other cereals, fallow lands, and legume crops like soybean and alfalfa (Bertoni et al., 2018, 2021).

2.2. Bird data

We obtained bird occurrence data from two breeding bird population monitoring programs ("Monitoraggio dell'avifauna nidificante in Lombardia" of Lombardy region administration and the "Farmland Bird Index" coordinated by LIPU/BirdLife Italia) aimed at assessing population trends of common breeding bird species in Lombardy. Field data were collected by experienced fieldworkers using the point counts technique, where all birds observed or heard within a fixed time frame (10 min) and a 100 m radius from the census points were recorded (Bibby et al., 2000; Gagliardi and Tosi, 2012). From the original dataset, we extracted data collected at 1808 point counts located within agricultural landscapes (based on point count geolocation) between 2010 and 2018, of which 519 were surveyed repeatedly for 2-9 years. To minimize biases, it is fundamental to consider only those species that are

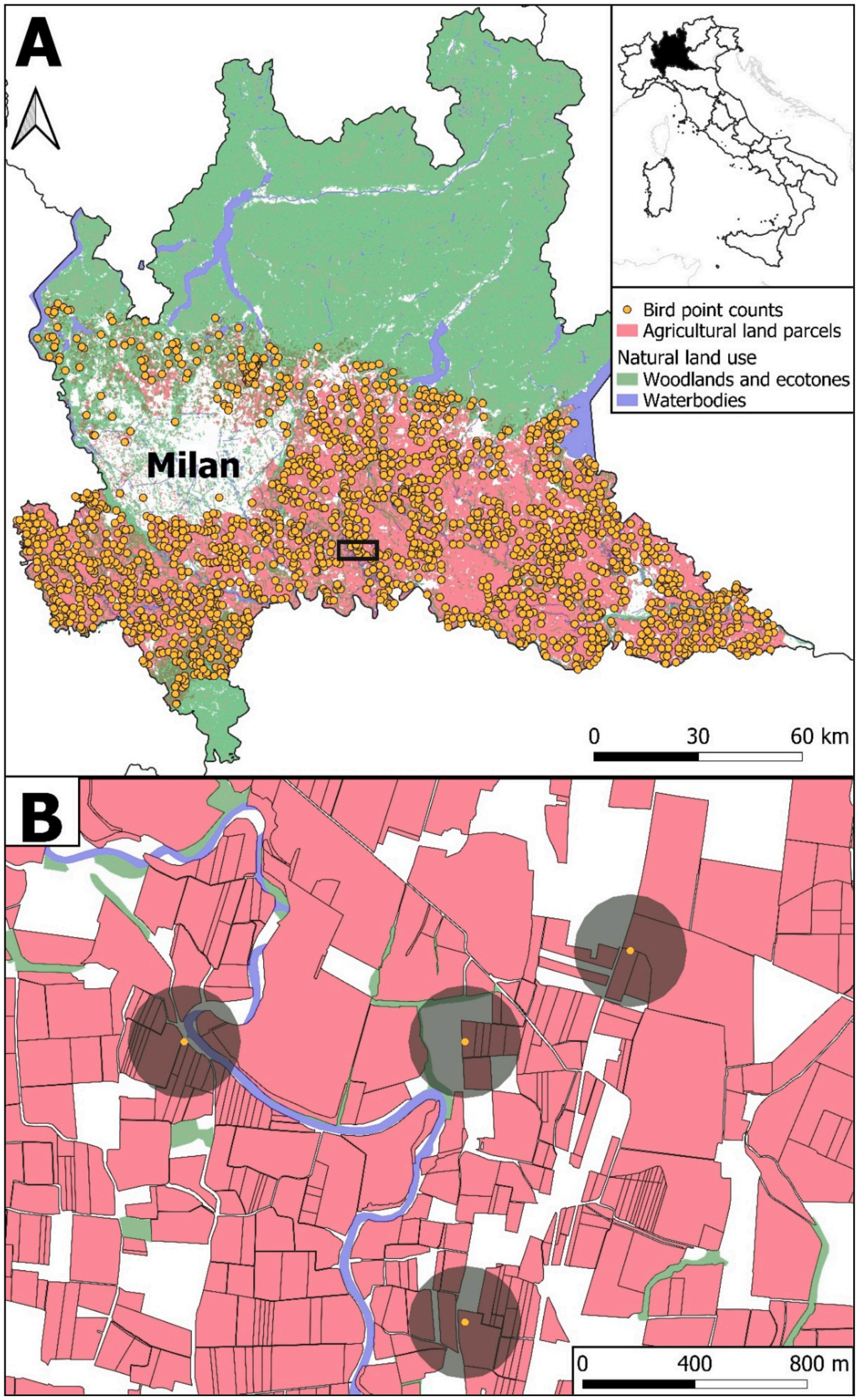

Fig. 1. A) map of the whole study area within the Lombardy region; B) close-up view of individual agricultural land parcels (in pink) and buffers (dark grey) surrounding bird point counts (orange dots). Blue indicates rivers and green indicates natural elements.

functionally associated with the survey sites (Gagliardi and Tosi, 2012). Thus, we excluded flying-over individuals and species that move between different habitats or only temporarily use agroecosystems, showing no or only weak ecological relationship with the habitats surrounding point counts (e.g., waterbirds, swifts *Apus* spp.; Cramp, 1998). In this way, we retained only the records of those species known to be related with agroecosystems for feeding and/or nesting (Cramp, 1998). Then, we classified species based on their trophic niche (granivores, insectivores) and habitat preferences (farmland specialists). We retrieved the trophic niche from the AVONET trait dataset (Tobias et al., 2022). We considered as farmland specialists all the species listed in the Italian Farmland Bird Index (Rete Rurale Nazionale and Lipu, 2024).

Given the type of census data (count of birds within a 100 m radius, without any information regarding the actual breeding status), it was not possible to obtain estimates of the actual abundance (i.e., density) of breeding individuals at the point count level. Since most species are territorial and the average size of a territory for small passerines is usually around 1 ha (Brambilla et al., 2024a), we assumed that if a given species was detected at a given site, irrespective of the numbers reported, it was likely to breed at that site with at least one territory/breeding pair. We then calculated for each point count and year four metrics of local bird communities, based on the functional characterization and ecological preferences: overall community species richness, farmland specialists richness, granivorous richness and insectivorous richness.

2.3. Farming practices data

We retrieved farm-level agronomic data for ~591,900 farmland parcels for the period 2011-2017 from Bertoni et al. (2018). For each farmland parcel in each year, we obtained data on its extension (in hectares), its corresponding farm, the type of cultivated crops (23 types), and the type of management practices applied (conventional, organic, integrated, or conservation-tillage farming). Data about farm adoption of integrated and conservation-tillage farming was derived from their participation in agri-environmental measures, provided by Lombardy RDP. A detailed description of all the requirements associated with these practices in Lombardy is provided in Table S1. For 2014, we also obtained data on parcel CAP compliance, i.e., whether the corresponding farm had to adapt to 2015 CAP greening reform, changing its previous management practices, or not. The latter was a binary variable where parcels belonging to non-compliant farms (i.e., farms that had to adapt to 2015 CAP greening reform) were assigned a value of 1, while parcels of farms which were already compliant or belonged to non-eligible farms, not requested to modify their usual practices, were assigned a value of 0. Finally, to reduce the complexity of the analysis, from the original set of 23 crop types, we obtained 10 different aggregated crop categories (Table S2).

From farm-level data, we calculated several agronomic variables within a 200 m buffer from each point count, which represents the approximate average foraging range or territory size of the studied species (Cramp, 1998). These were: the relative extent (%) of each aggregated crop category, the presence of organic, integrated, and conservation-tillage farming practices within the buffer, and crop diversification level. Crop diversification was calculated on the original set of 23 crops using the Shannon Diversity Index, which reflects crop heterogeneity within the landscape (Josefsson et al., 2017). We also accounted for the maintenance of natural elements by quantifying the relative extent (%) of natural habitats (woodlands, ecotones, and wetlands) in each buffer. We derived information on the spatial location and extension of natural habitats from 2012 to 2015 land use maps of the Lombardy region (http://www.cartografia.regione.lombardia.it; ground resolution: 3 m), and we assigned to each year the value of the temporally nearest map (Dalpasso et al., 2022).

2.4. Statistical analysis

We relied on Generalized Linear Mixed Models (GLMMs) to evaluate the overall association between sustainable farming practices envisaged by both CAP pillars and bird species richness metrics (cross-sectional analysis), as well as the impact of the implementation of greening practices promoted by 2015 CAP reform (longitudinal analysis). Models were fitted separately for overall community species richness, and the richness of farmland, granivorous, and insectivorous species respectively.

In the cross-sectional analysis, relying on a total of 2836 point counts-year combinations, we investigated the association between sustainable farming practices and richness metrics, using a negative binomial distribution to account for overdispersion in the response variable. Crop diversification, natural habitat extent, and the occurrence (absence = 0, presence = 1) of organic, integrated, and conservation-tillage farming practices were included as predictors in all four GLMMs. To control for potential confounding agronomic factors, we incorporated additional covariates representing the relative extent of the most relevant aggregated crop categories (maize, rice, other cereals, grasslands, legumes and tree crops). To account for possible temporal trends in species richness, we included the year of monitoring as a covariate. Finally, to account for the hierarchical structure and spatial autocorrelation in the data, we incorporated random intercepts for point count identity and year and a spatially structured random effect using the Besag spatial model (Besag et al., 1991). We also tested the interactions between organic, integrated, conservation-tillage farming and the aggregated crop categories in which these practices were most frequent (Figs. S1–S3). None of these interactions showed statistically significant effects, thus we excluded them from the analyses presented in the main text.

Cross-section analyses are useful to assess overall spatial patterns, but longitudinal analyses of temporal changes are needed to confirm that management practices actually result in positive impacts on biodiversity (Boënnec et al., 2024; Yoccoz et al., 2001). In the longitudinal analysis, we tested whether 2015 CAP reform, which promoted the implementation of greening practices, affected local species richness metrics. In this analysis, we considered only point counts surveyed at least once before (2010–2014) and after (2015–2018) the introduction of 2015 CAP reform, resulting in a total of 875 point counts-year combinations.

First, we checked whether sustainable agricultural practices and the extents of the most relevant aggregated crop categories changed over time in the buffers surrounding the 875 replicated point counts. To this end, we fitted ten GLMMs alternatively using as dependent variables: the presence of organic, integrated, and conservation-tillage farming practices, crop diversification, and the relative extent of maize, rice, other cereals, grasslands, legumes and tree crops. In these models, the year of monitoring was the only predictor, while point count identity was included as a random intercept. Since the relative extent of crops was expressed as proportions bounded between zero and one, we modelled them using a beta distribution (Gómez-Déniz and Sarabia, 2018). The response variables were rescaled to avoid fixed zeros and ones following Smithson and Verkuilen (2006).

Subsequently, we assessed whether the implementation of greening practices, introduced for the 2015-2022 CAP programming period, promoted bird species richness. Due to the conditionality of Pillar I CAP direct payments, almost all farms non-compliant to greening had implemented greening practices since 2015 (Bertoni et al., 2021). We thus expected that bird communities responded by showing a relative increase of species richness after implementation of the CAP reform, and that the extent of such relative increase should be proportional to the extent of farmland in the landscape surrounding the point count that was subjected to greening practices. Therefore, to test the effects of CAP greening implementation on richness metrics, for each buffer we calculated a “CAP surface” variable, defined as the relative extent (%) of farmland that had adapted to the 2015 CAP greening reform (Šumrada et al., 2021). We fitted four GLMMs, one for each richness metric, where we included as predictors the “CAP surface” variable, a binary variable (“CAP reform”) indicating whether the survey was conducted before (0) or after (1) CAP greening implementation (i.e. before 2015 or after 2014), and their interaction. We also included point count identity as random intercept. The interaction between “CAP surface” and “CAP reform” tested if and how richness metrics changed according to the extent of agricultural area where greening practices were applied after 2015 CAP reform. For instance, while before 2015 the association between the agricultural extent to be adapted and diversity metrics was expected to be negative, reflecting the overall negative effects of intensive farming on biodiversity, such negative association could be relaxed or even disappear after 2015 thanks to the introduction of greening practices, which may mitigate the negative effects of intensive agriculture. Finally, considering that the proximity of a protected area can influence local biodiversity dynamics (Cazalis et al., 2020), we further tested whether being located within or in proximity to a Special Protection Area (SPA, i.e. an area where conservation measures targeting bird species of EU conservation interest are implemented under EU Birds Directive 2009/147/EC; Donald et al., 2007) affected bird richness. To this end, we added a binary variable assigning a value of 1 to point counts located within a 500 m buffer from a SPA and 0 otherwise (Brambilla et al., 2024a).

We fitted all models in a Bayesian framework using the Integrated Nested Laplace Approximations (INLA) approach with default uninformative priors, as implemented in the R package *INLA* (Bivand et al., 2015). INLA enables an accurate approximation of the posterior distributions in models with complex spatial structures, while considerably reducing computational load and solving convergence issues (Rue et al., 2009).

Before running the analyses, we checked for multicollinearity by calculating the Variance Inflation Factor (VIF) using the R package *car* (Fox and Weisberg, 2019). The VIF is an index that quantifies how much the variance of a regression coefficient is increased due to multicollinearity among the predictors (Dormann et al., 2013). Multicollinearity is normally considered an issue when VIF > 2.5 (Johnston et al., 2018), but our set of predictors did not show any multicollinearity problems (Table S3). All predictors were standardized (mean = 0, SD = 1) to facilitate model convergence and enable the comparison of effect sizes among predictors.

3. Results

3.1. Avian surveys

Overall, 133 breeding bird species were recorded. The most frequent ones were the hooded crow (*Corvus cornix*; 85% of point counts across all years), the common starling (*Sturnus vulgaris*; 82%), the Eurasian blackcap (*Sylvia atricapilla*; 71%), the common blackbird (*Turdus merula*; 69%) and the barn swallow (*Hirundo rustica*; 64%). Overall community richness across point counts was highly variable (8.5 ± 4.64 SD species), while among specific groups farmland specialists showed highest richness values (3.95 ± 2.27 SD species), followed by insectivores (2.37 ± 1.85 SD species) and granivores (1.15 ± 1.13 SD species).

3.2. Sustainable farming practices and bird species richness

Cross-sectional analyses revealed that sustainable farming practices envisaged by both CAP pillars had different associations with species richness metrics, with only a few variables showing consistent associations (Fig. 2; Table S4). Crop diversification was the only sustainable farming practice that showed a positive association with all richness metrics, while the maintenance of natural elements (represented by natural habitat extent) showed a positive association with overall community and insectivorous species richness, but it showed a negative association with the richness of farmland specialists and granivores. Integrated farming showed a positive association with the richness of farmland specialists, and organic farming showed a positive association with overall community and insectivorous species richness.

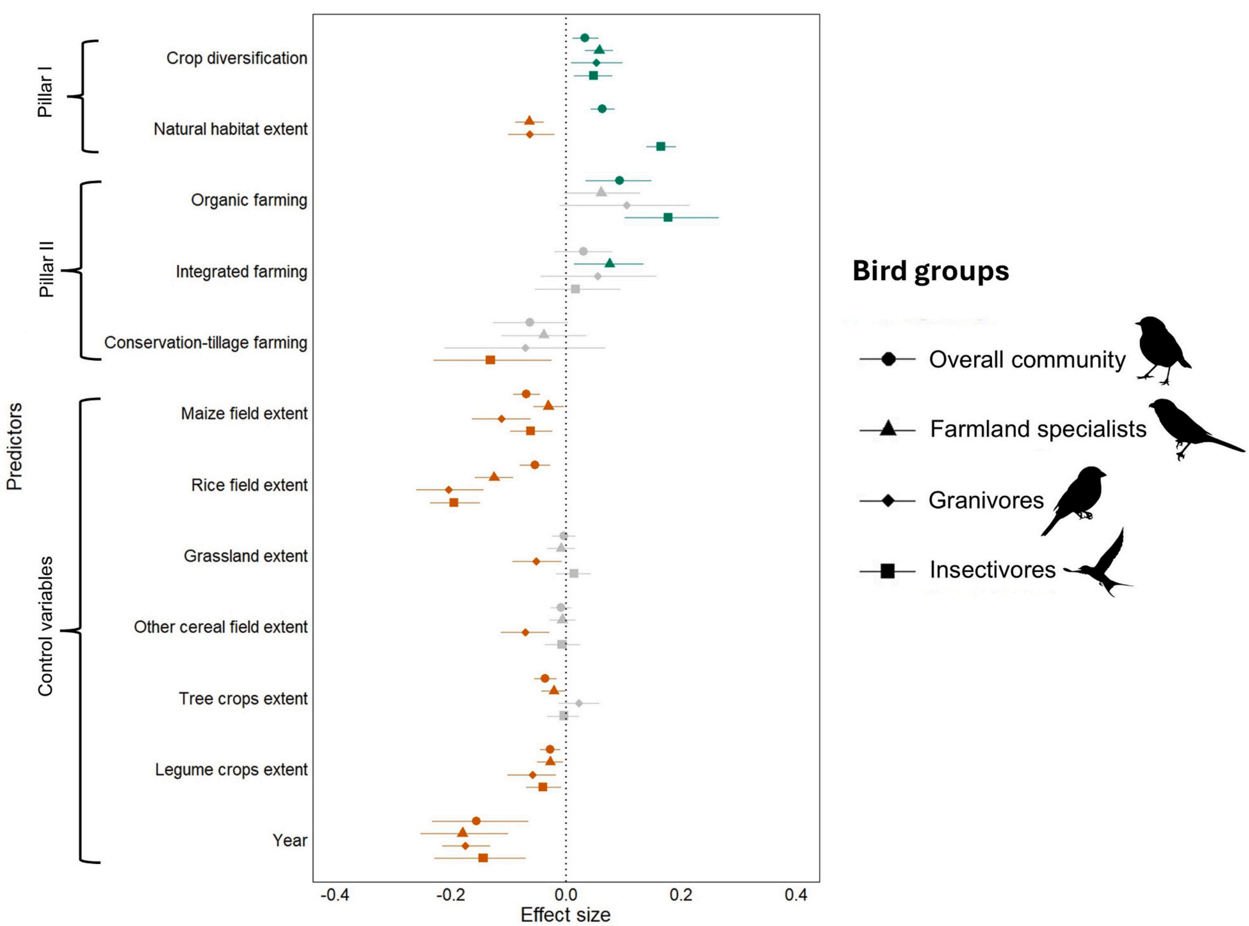

Fig. 2. Posterior distribution (dots: median; bars: 95% credible intervals) of the association between agronomic variables and avian species richness metrics (overall community, farmland specialists, granivores, and insectivores). Green and red symbols indicate positive and negative associations respectively, while grey symbols denote associations whose 95% credible intervals overlap zero.

Conservation-tillage farming was the only sustainable agricultural practice that showed a negative association with the richness of insectivorous species (Fig. 2; Table S4).

The associations between crop extents and species richness metrics were more consistent (Fig. 2; Table S4). Maize, legume and rice fields extents showed a negative association with all metrics. The extent of other cereals showed a negative association with granivorous richness. Tree crops showed a negative association with overall community richness, while grassland extent showed a negative association with granivorous richness (Fig. 2; Table S4).

Finally, a general decrease in bird species richness over time emerged, which was similar among all richness metrics but somewhat more pronounced for farmland specialists (Fig. 2; Table S4).

3.3. Temporal changes of farming practices and bird species richness

The longitudinal analyses on the changes of farming practices in the landscape surrounding replicated point counts revealed an increase of crop diversification and organic farming through time, while conservation-tillage and integrated farming did not change (Fig. 3; Table S5). Among crops, maize cultivations decreased while grasslands increased. The extents of rice fields, other cereals, legumes and tree crops did not change over time (Fig. 3; Table S5).

The longitudinal analyses also revealed a positive interaction between "CAP surface" and "CAP reform" on overall community species richness (estimate = 0.2, 95% C.I. = 0.01 to 0.39; Fig. 4; Table S6). While before 2015 the association between CAP surface and species richness was negative (estimate = −0.26, 95% C.I. = −0.5 to −0.02), as expected from the generally negative effect of agricultural intensification on bird diversity, since 2015 such association became shallower, with 95% C.I. overlapping zero (estimate = −0.05, 95% C.I. = −0.3 to 0.18), suggesting that greening measures effectively mitigated the negative impact of intensive farming practices on overall bird community species richness (Fig. 4; Table S6). No effects of CAP surface, CAP reform or their interaction were detected for the other three species richness metrics in this small subset of repeated point counts (Fig. 4; Table S6). The proximity to SPAs did not show any effect on bird diversity, as 95% C.I. broadly overlapped zero for all metrics (Table S7).

4. Discussion

We assessed the associations between several biodiversity-friendly farming practices envisaged by both CAP Pillar I (crop diversification, maintenance of natural elements) and Pillar II (organic, integrated, conservation-tillage farming) and diversity indicators of avian communities related to different ecological and functional traits (overall community species richness, richness of farmland specialists, granivores and insectivores). Then, we tested whether the implementation of greening practices promoted by the 2015 CAP reform enhanced their diversity. Avian communities were more diverse in areas with higher crop diversification, while the association with other environmental-friendly practices (maintenance of natural elements, organic, integrated, and conservation-tillage farming) varied among different richness metrics. The adoption of greening practices promoted by the 2015 CAP reform, though insufficient to prevent the declines of farmland species, effectively mitigated the negative effects of intensive farming on overall community species richness.

4.1. Farming practices and avian communities

Among the sustainable farming practices envisaged by CAP Pillar I, crop diversification was the only one that showed a consistent positive association with all diversity metrics, confirming that this strategy could mitigate the negative effect of intensive agriculture on biodiversity (Assandri et al., 2016; Fahrig et al., 2011; Frank et al., 2024). Crop diversification can play a key role by providing complementary resources and habitats for species with different ecological needs (Kremen and Merenlender, 2018). These additional resources are particularly relevant in the agricultural landscape of Lombardy, where agricultural intensification led to a degradation of the remaining lowland natural habitats. The maintenance of natural elements showed different responses across metrics. Birds generally benefit from the presence of natural elements in agricultural landscapes, as these generally offer a better-quality habitat for feeding and nesting (Assandri et al., 2016; Brambilla et al., 2015). However, their presence or expansion in agroecosystems can limit the occurrence of certain farmland species that are associated with open habitats (Báldi and Batáry, 2011; Brambilla et al., 2020). Many of these species are experiencing severe population declines (Rete Rurale Nazionale and Lipu, 2024), highlighting the need for targeted conservation measures.

Agri-environmental measures envisaged by CAP Pillar II exhibited different responses among bird species richness metrics. Organic farming showed a positive association with overall community and insectivorous species richness, and can be interpreted as the combined result of the use of non-synthetic agrochemicals and crop rotation. Birds are known to be positively affected by organic farming, as the prohibition of synthetic agrochemicals increases food availability and reduces pesticide exposure (Barbaro et al., 2021; Moreau et al., 2022), particularly benefitting insectivores because of their specialized diet (Genghini et al., 2006). Moreover, crop rotation can further enhance local habitat heterogeneity and thus increase bird diversity (Das et al., 2025). Integrated farming is also known to benefit bird diversity (Katayama et al., 2019), though its effectiveness is more variable as different farming practices can be applied depending on the country or region (Genghini et al., 2006; Štefanová and Šálek, 2014). In our context, the observed positive association with the richness of farmland specialists can be attributed to the reduced input of agrochemicals (Genghini et al., 2006). Finally, we found a negative association between conservation-tillage farming and insectivorous richness. This practice is known to have generally positive impacts on birds due to an increased availability of prey (arthropods and earthworms) and nesting sites because of minimum soil tillage (Filippi-Codaccioni et al., 2009; Hutcheon et al., 2001). However, conservation-tillage is also one among many agronomic practices aimed at controlling weed-crop competition, which requires the adoption of specific practices (increased use of herbicides and/or cover crops) fundamental to maintain soil fertility and avoid severe crop yield losses (Dong et al., 2024). According to Barré et al. (2018), such weed management practices associated to conservation-tillage have opposite effects on insectivores: negative in case of herbicide use and positive in case of cover crops before and after the main crops. It is therefore plausible that the negative association with insectivorous richness reflects the negative impact that herbicides can have indirectly on insectivores by reducing the availability of preys (Barré et al., 2018).

The consistent negative association between bird richness and the extents of cultivated lands is likely due to the intensive management of these crops – particularly rice and maize – thereby reducing habitat suitability for most bird species (Assandri et al., 2016; Dalpasso et al., 2025; Sauerbrei et al., 2014). Grasslands did not show positive association with any of the considered metrics, although this would have been expected since these agroecosystems are among the richest in bird diversity in Europe (Conti et al., 2026; Dengler et al., 2014). This could be due to the strong intensification that many Italian grasslands have undergone in the last decades, leading to ecological degradation and less suitable conditions for many birds (Assandri et al., 2019).

4.2. Temporal changes in farming practices

Our results confirmed that, among sustainable farming practices, surfaces devoted to crop diversification and organic farming increased around repeatedly surveyed point counts, while areas under integrated and conservation-tillage farming did not change. These changes were accompanied by a reduction in maize cultivations and an increase in

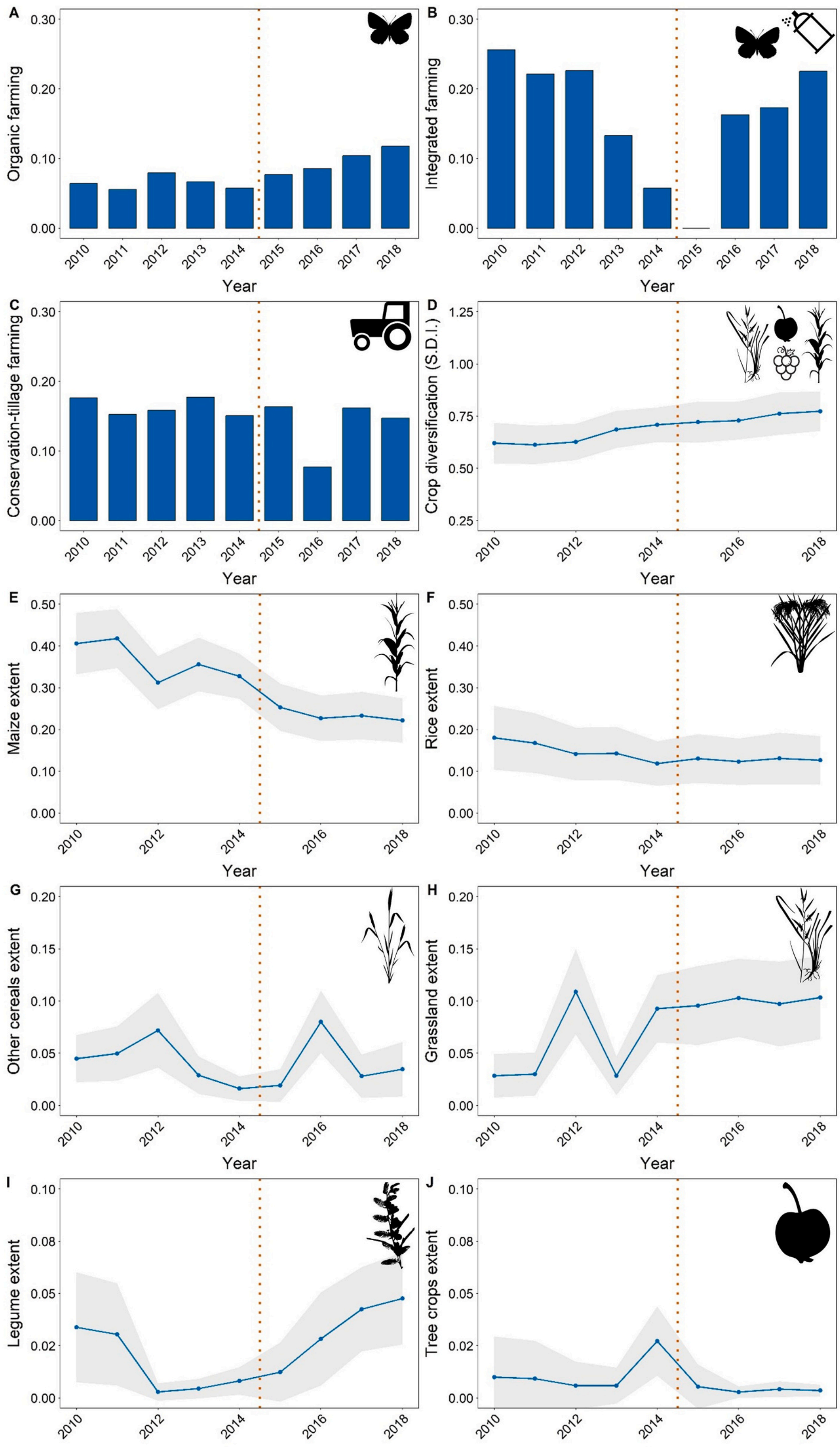

Fig. 3. Temporal variation of A) organic farming, B) integrated farming, C) conservation-tillage farming, D) crop diversification, E) maize extent, F) rice extent, G) other cereals extent, H) grasslands extent, I) legume extent and J) tree crops extent in the landscape surrounding 875 point counts-year combinations (surveyed both before and after CAP implementation). The red dotted line corresponds to the introduction of the 2015 CAP reform.

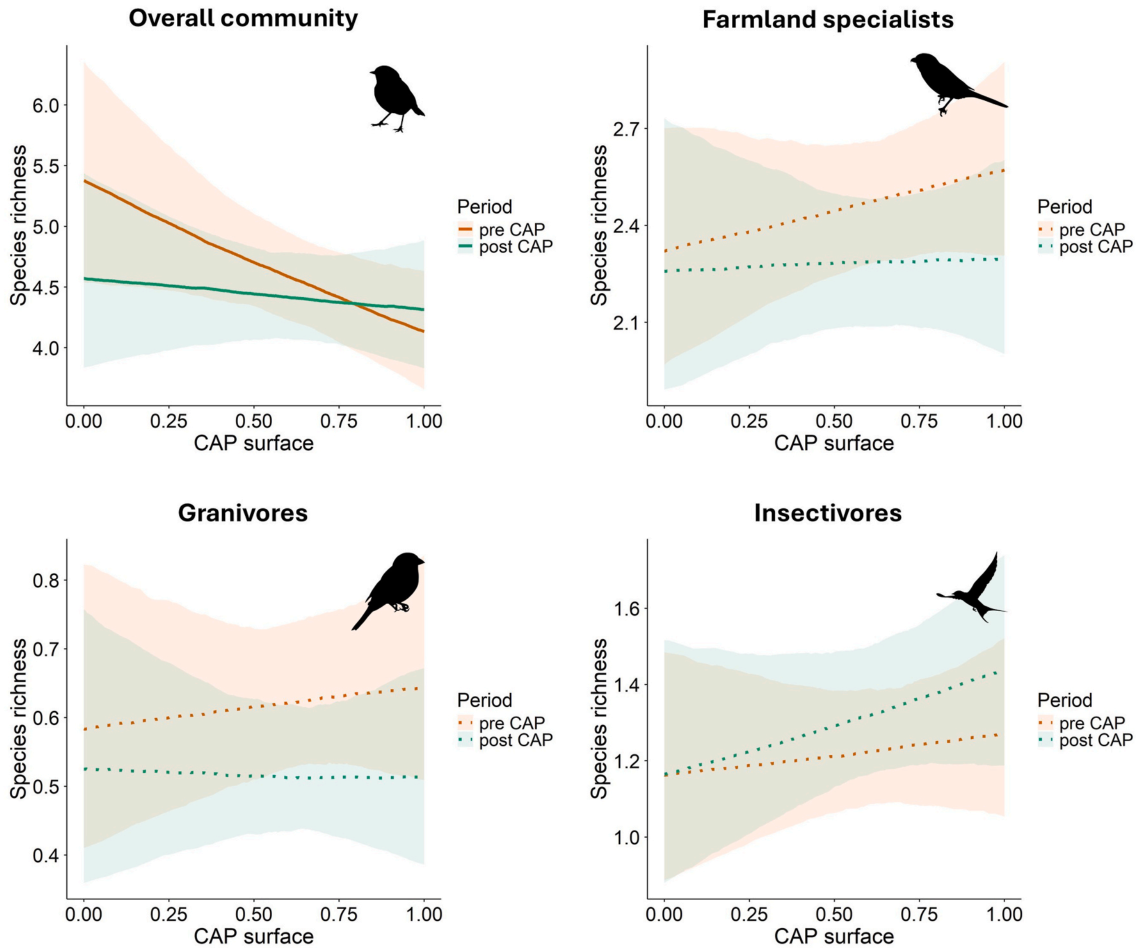

Fig. 4. Predicted species richness (median and 95% C.I.) as a function of CAP surface before (red) and after (green) the implementation of 2015 CAP greening reform for A) overall bird community, B) farmland specialists, C) granivores and D) insectivores. Dotted lines indicate that the 95% C.I. of the effect of CAP surface on species richness overlaps zero.

grasslands, while the other crops did not change their extent. These results align with previous findings on a regional scale, which revealed that 2015 CAP greening reform led to an increase of crop diversification driven by a reduction in maize monoculture, favoring other cereals and legumes (Bertoni et al., 2018). The small observed increase in grassland extent can also be attributed to the 2015 CAP greening reform, as for this crop an increase between 10 and 20% was predicted from *ex ante* simulations (Cortignani et al., 2017; Solazzo et al., 2015). The increase in organic farming was probably driven by the RDP (CAP Pillar II), which included dedicated operations that contributed to the growing adoption of organic farming in Italy (Casolani et al., 2021). Integrated and conservation-tillage farming did not show substantial changes through time, although integrated farming strongly decreased in 2014-2015. This decrease is due to the pause of public incentives for this measure between the 2007-2013 and 2014-2020 RDP programming periods (contracts for the latter programming period actively started in 2016).

4.3. Effects of 2015 CAP greening reform on bird species richness

Longitudinal analyses confirmed that the 2015 CAP greening reform, by fostering crop diversification, permanent grassland maintenance and ecological focus areas, positively affected overall community richness. While before the CAP reform, farmlands subject to greening practices showed fewer species than farmlands already compliant, after their implementation there were no differences in species richness among farmlands. This means that the implementation of greening practices enhanced habitat quality of those farmlands and benefited bird communities, filling the gap between formerly non- and already-compliant farms. Still, although these practices benefited avian diversity, they appeared insufficient to counteract the long-term declines observed over the recent decades (Pe'er et al., 2014). Indeed, in our dataset, the share of grassland extent was still low despite the increase (less than 10%), and even crop diversification only slightly increased. Criticisms about the effectiveness of CAP for biodiversity suggested that the lack of benefits is due to low requirements and broad exemptions in CAP compulsory instruments, as well as the imbalanced investment in the environment compared to other objectives (Pe'er et al., 2019, 2014). For example, the share of ecological focus areas was set at 5% of farmland and only for farms exceeding 15 ha; moreover, nitrogen-fixing and catch crops could be qualified as ecological focus areas. Despite these crops can help maintain soil and water quality, they are not known to benefit biodiversity as they do not provide additional habitat (Dicks et al., 2014). Similarly, regarding the maintenance of permanent grasslands, no differentiation among grassland type was specified, so any grassland type contributes to the overall grassland share regardless of their biodiversity value (Pe'er et al., 2014), despite huge differences from a bird conservation perspective (Assandri et al., 2019). Moreover, no prescriptions about grassland management were included, potentially turning some subsidies intended to promote grassland conservation into harmful measures for grassland birds at regional scale. For instance, in a neighboring area in northern Italy (Trento province), subsidies promoting grassland mowing as a measure to encourage the maintenance of grasslands lacked any regulation of mowing time and methods. By indirectly promoting widespread and simultaneous mowing over large areas, the widespread adoption of these incentives negatively impacted the ground-nesting corncrake (*Crex crex*), a species of conservation interest in the EU (listed in the Annex I of the Birds Directive), because mowing occurred during the breeding season and nests were frequently destroyed (Brambilla and Pedrini, 2013).

All the above limitations might have played a key role in constraining positive effects of crop diversification, grassland increase, and organic farming on avian communities. This likely reflects the fact that the CAP was originally designed to support agricultural income, with environmental goals gradually added over time. Therefore, while the measures introduced to enhance the environmental sustainability of agriculture may look insufficient to long-term biodiversity preservation in agroecosystems, they were the result of efforts to strike a balance between environmental and socio-economic objectives.

4.4. Study limitations

Despite our findings provide useful insights, some limitations should be acknowledged. These are mainly the relatively short duration of the post CAP greening reform monitoring period and the reliance on species richness as the only biodiversity metric. While birds exhibit relatively rapid responses to management interventions (Brambilla et al., 2024b), the rate of change is highly influenced by the functional/trophic group considered (Brambilla and Gatti, 2022). Thus, the relatively short post CAP greening reform evaluation period could have hampered our ability to detect species richness changes within specific avian guilds. Moreover, species richness captures only a frame of overall biodiversity, as it does not provide information on species abundance or identity (Fletcher et al., 2025). Thus, while species richness might not exhibit short-term changes within a site, species abundance or turnover may be affected (Magurran et al., 2018). Including fine-scale estimation of abundance and community metrics in a longer duration study will complete our understanding of the effect of 2015 CAP reform on overall bird diversity. Finally, farmers' environmental beliefs and cultural context can have important implications on the outcome of agri-environmental practices (Lastra-Bravo et al., 2015; Wang et al., 2023). For example, sustainable measures often attract farmers who have already adopted these practices in the past, subsidizing existing environmental-friendly behaviors rather than generating new environmental gains (Bertoni et al., 2020). Accounting for farmers' attitudes toward sustainable agri-environmental practices could provide further insight into how to plan future CAP reforms.

5. Conclusions

Our study showed that sustainable farming practices like crop diversification, the maintenance of natural elements, organic and integrated farming generally showed positive associations with avian diversity metrics. The 2015 CAP greening reform promoted crop diversification, the maintenance of permanent grassland and ecological focus areas, with detectable positive effects on overall community species richness. These results highlighted that these measures were potentially valid for enhancing bird diversity, but were insufficient to buffer long-term negative biodiversity trends in agroecosystems (Pe'er et al., 2022).

This raises the question of how to improve the effectiveness of CAP expenditure devoted to agrobiodiversity in future programming periods. First, financial resources should concentrate on the most effective agri-environmental measures, i.e. those known to increase biodiversity, maximizing conservation impact. Among them, the maintenance of natural elements (e.g., hedgerows, woody and flower strips, ditches) and of permanent grasslands, integrated and organic farming should be favored (Anderle et al., 2025; Rigal et al., 2023; Rodríguez-Gasol et al., 2026; Vallé et al., 2023). However, several studies indicate that farmers tend to avoid overly demanding agri-environmental measures because of the difficulty and long-term commitments they entail (Schaub et al., 2023; Tyllianakis et al., 2025). So, new strategies need to be employed to increase farmers' participation and achieve impacts at meaningful scales. A possible way to maximize the uptake of effective CAP environmental instruments should involve a comprehensive revision of how agri-environmental payments are proposed to farmers. The widespread adoption of some CAP 2023-2027 eco-schemes suggests that incentivizing the adoption of environmental measures, rather than imposing them, could enhance farmers' uptake of biodiversity-friendly practices (OECD, 2025). The recently released 'Vision for Agriculture and Food' by the EU Commission, which sets the direction for the forthcoming CAP 2028–2034, indeed envisages a shift for the future CAP from a system based on conditions toward one based on incentives in addressing environmental goals (EU Commission, 2025). Within this framework, an approach could entail the replacement of current agri-environmental payments, whose amount is calculated solely on higher costs and foregone revenues with respect to standard farming practices, incurred by farmers adopting agri-environmental measures, with enhanced incentive-based payments. These payments would incorporate an additional incentive component beyond higher adoption costs and foregone revenues in exchange for the adoption of science-based agri-environmental practices that actually promote biodiversity. As shown in other EU member states, result-based payments could potentially contribute to these purposes (Schaub et al., 2025). The need to focus limited resources on the most effective policy instruments is even more necessary, given the changes in CAP structure and the announced budget restrictions after 2027, which may dampen CAP environmental ambitions.

CRediT authorship contribution statement

Andrea Dalpasso: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Danilo Bertoni:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Giacomo Aletti:** Resources, Data curation. **Gianpiero Calvi:** Writing – review & editing, Resources, Data curation. **Daniele Cavicchioli:** Writing – review & editing, Funding acquisition, Conceptualization. **Claudio Celada:** Resources, Data curation. **Mattia Falaschi:** Writing – review & editing, Supervision, Conceptualization. **Federica Luoni:** Writing – review & editing, Resources, Data curation. **Roberta Righini:** Writing – review & editing, Resources, Data curation. **Diego Rubolini:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Andrea Simoncini:** Writing – review & editing, Data curation. **Gentile Francesco Ficetola:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Mattia Brambilla:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130933.

Data availability

The final dataset is available at figshare (https://doi.org/10.6084/m9.figshare.33723694).

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