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Research Article

Phenology of migrating game birds in Italy based on citizen science data

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Studying the timing of the seasonal movements of migratory birds, known as migration phenology, is crucial for managing and conserving migratory bird populations. This is particularly important for migratory game bird populations in Europe because, according to the EU, migratory birds should not be hunted during their breeding season or during return movements to breeding grounds (pre-breeding or pre-nuptial migration). To effectively protect these species during these critical periods, it is vital to employ reliable methods for assessing their migration phenology. Citizen science, which involves the participation of skilled volunteers in scientific data gathering, is a valuable resource for migration studies. It allows the collection of large amounts of data across extensive geographic areas, overcoming some limitations of other datasets and analytical methods. In this study we analysed pre- and post-breeding migration phenology of 23 game bird species in Italy, using citizen science data from the www.Ornitho.it portal. We then compared our findings on pre-breeding migration onset with published migration timing data from ringing records and found a close match. Additionally, we compared our results with the pre-breeding migration onset determined for Italy in the 'Key Concepts Document' (KCD) published by the European Commission that plays a central role in the regulation of hunting activities in EU countries. For 19 species (83%), we estimated an earlier pre-breeding timing compared to that reported in the last KCD for Italy (2021, amended in 2025 for four species), highlighting a potential risk of these species being hunted during their pre-breeding migration. These findings highlight the value of citizen science data in obtaining migration timing and the

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importance of employing multiple methods to estimate it. This approach is particularly valuable for species subject to hunting, which require well-informed management.

Keywords: EU Birds Directive, Key Concepts Document, post-breeding migration end, pre-breeding migration onset, sustainable hunting

Introduction

Every year, billions of birds move across continents as the season changes, in search of optimal breeding or non-breeding grounds (Hahn et al. 2009). The timing of these seasonal movements, known as migration phenology, plays a crucial role in various biological processes. Migration timing can affect the fitness and survival of migratory birds, as there is often an 'optimal time window' when environmental conditions are most favorable (Miller-Rushing et al. 2010, Visser and Gienapp 2019). Studying migration phenology is therefore crucial for informing policies aimed at the management and conservation of migratory bird populations. In the European Union (EU), bird conservation is regulated through the Birds Directive (Directive 2009/147/EC) which provides a legal framework to protect bird populations and their habitats. As specified in the Key Concepts Document (KCD) of Art. 7(4) of the Birds Directive, the directive prohibits the hunting of migratory birds 'during their return to their breeding grounds', i.e. during pre-breeding migration (Art. 7.4). This regulation is founded on the ecological principle that protecting birds during their pre-breeding migration increases breeding success in the following nesting season. Consequently, the KCD plays a vital role in shaping hunting regulations by defining the start of the hunting season for each game species within every EU Member State (hereafter Member State).

To implement this directive, the European Commission (the executive branch of the European Union) assigned the Member States the task of identifying the specific 10-day periods (or 'decades', as defined in the European Commission's hunting guidelines, where each month is divided into two 10-day periods and one final period of 8–11 days, depending on the month's length) marking the onset of pre-breeding migration for each quarry species within their territories. This information was formalized in the KCD in 2001 and underwent updates in 2009, 2014 and 2021, following a comprehensive revision process involving all Member States (European Union 2021). This was done by comparing different sources of data from different regions of the European Union, including analyses of ring recoveries, satellite tracking studies, citizen science data and arrival dates in the breeding areas (European Union 2021). In 2025 Italy updated its KCD for four species (Note of the Italian Ministry of Environment and Energy Security, id number TBM-267_2025-0089, 19/02/2025). Despite these efforts, discrepancies in defining pre-breeding migration periods persist between neighbouring countries due to differences in datasets and methods (Andreotti et al. 2023). Comprehensive knowledge of migration timing could help Member States determine the optimal opening of the hunting season (Lehikoinen and Jaatinen 2012), particularly for species with local breeding populations that are vulnerable to hunting pressure. Therefore, ensuring the use of reliable methods to study migration phenology is imperative for effectively conserving quarry species.

Advances in remote tracking technology now allow accurate estimation of migratory birds' departure and arrival dates (Kays et al. 2015, Wilmers et al. 2015, Ng et al. 2018). However, tracking devices may affect birds' behaviour, health, and survival (Geen et al. 2019), with impacts likely underestimated under certain environmental conditions (Bodey et al. 2018, Gillies et al. 2020, Cleasby et al. 2021, Portugal and White 2022). Moreover, tracking data are often limited to just a few individuals in a restricted area (Bridge et al. 2011), making population-level inferences on migration timing from these results unrealistic for many species.

Another method for studying migration phenology relies on capturing either the initial arrivals or final departures of ringed birds from their breeding or wintering grounds (Thorup et al. 2014, Haest et al. 2018, Lawrence et al. 2022). Most existing knowledge of bird migration is based on ringing data, a technique developed in 1899 that enables individual identification through uniquely coded metal rings attached to the leg. Bird ringing remains one of the most widely used methods in ornithology worldwide, as it is inexpensive, applicable to all bird species, and well-suited for long-term, large-scale studies. Consequently, ringing data have historically formed the basis of migration atlases (Wernham et al. 2002, Spina and Volponi 2008a, 2008b). Nonetheless, these data are constrained by geographic sampling biases (Thorup et al. 2014). Hence, data obtained from both tracking devices and ringing present different constraints that limit the study of migration timing across vast geographical areas.

The growing prevalence of data collected by citizen scientists, particularly amateur birdwatchers, holds the potential to mitigate some of these constraints. Each year, citizen science projects contribute millions of bird species observations, providing data at a greater spatial scale than ringing recoveries (Newson et al. 2016, Chandler et al. 2017, Pocock et al. 2018, Passarotto and Costanzo 2024). This enables scientists to analyse the migratory movements and migration phenology of species on a larger scale (Hurlbert and Liang 2012, La Sorte et al. 2017, Schubert et al. 2019, Ambrosini et al. 2023, Border et al. 2024). However, citizen science data also exhibit spatial and temporal biases, as the timing and locations of observations are determined by the participants, leading to uneven sampling effort across time (e.g. weekends versus weekdays) and space (e.g. densely populated versus remote areas) (Johnston et al. 2023). Since the early 2000s complete list citizen science data, such as EuroBirdPortal (https://eurobirdportal.org/ebp/en) and eBird, have become a useful source of our knowledge on migration timing (Sullivan et al. 2009). Despite the potential for species misidentification (Gorleri and Areta 2022), it has been demonstrated that both structured and unstructured citizen science data (where observers decide where, when, how and whether to record different species) can provide reliable information (Jackson et al. 2015, Kosmala et al. 2016, Kelling et al. 2019, Feng and Che-Castaldo 2021, Weisshaupt et al. 2021).

Each method has its own strengths and limitations, and studies that combine different data types to study migration timing (Heim et al. 2020, Weisshaupt et al. 2021, Ambrosini et al. 2023) hold great potential to evaluate and compare the spatial and temporal biases of different methodological approaches. For example, Kelly et al. (2016) used both observational data from eBird (www.ebird.org), a widely used database among birdwatchers, and remote sensing data from weather surveillance radars to analyse the timing of large-scale avian pre-breeding migration in the eastern United States. The two data sources provided similar results, supporting the use of citizen science data.

Our study aims to apply a recently developed method by Ambrosini et al. (2023) to analyse migration phenology of 23 migratory bird species that can be legally hunted in Italy using citizen science data from the www.Ornitho.it databank. This platform serves as a shared resource for ornithologists and birdwatchers and is supported by several national and regional ornithological associations dedicated to the study and conservation of birds and the promotion of birdwatching. Our analysis covers the Italian peninsula and the islands (Sardinia, Sicily and the minor Italian islands). To assess the robustness of our results, we compared the earliest calendar dates of pre-breeding migration onset in Italy, as estimated in this study with those obtained from published migration timing maps based on ringing data. These maps are reported in the research module on the migration season of hunted species (Bairlein et al. 2022) within the Eurasian African Bird Migration Atlas (Spina et al. 2022). Finally, we compared the 10-day period of migration onset in Italy derived from our results with the 10-day periods specified by the KCD (European Union 2021).

Methods

Pre-breeding migration timing

We retrieved the data available on the Ornitho.it databank for the species listed in Table 1. The data cover the years 2009 to 2023 (see Table 1 for details on the time span for each species and sample size). No filtering was applied to the data, as we were interested in the location and date of observation of these species. This included records both from complete checklists and occasional observations.

The analyses are based on the approach first proposed by Ambrosini et al. (2014) and refined to fit partial migratory species and citizen science data by Ambrosini et al. (2023). The study area (the Italian peninsula and Sardinia, Sicily and the minor Italian islands) was first divided into cells of 0.5 by 0.5° degrees (latitude – longitude), corresponding to approximately 50 × 40 km (north–south × east–west) at the latitudes of the study area. Cells containing fewer than 20 records collected in fewer than 10 different days in a year (the minimum required sample size) were merged with adjacent cells until the resulting cell included the minimum sample size reported above (full details are reported in the Supporting information). This procedure, identical to the one used in Ambrosini et al. (2023), ultimately generated cells of different sizes, inversely proportional to data density. Data that were spatially isolated were also identified and discarded to avoid the generation of unreasonably large cells. An example of the merged cells obtained for the Eurasian skylark is shown in Fig. 1.

It is important to note that records from all years were considered, irrespective of the year of observation. The number of records per day was then transformed first into the proportion of records per calendar date and then into the cumulative proportions of records at each date and cell. These were then modelled using a binomial generalized linear mixed model (GLMM) with a cloglog link function and exponential spatial covariance structure to account for spatial autocorrelation in the data. Day-of-the-year (centred to its mean value) was the only fixed predictor, while the random part of the model included cell ID as a random factor. In addition, the random part included a random slope for the day-of-the-year within cell (i.e. random intercept and slope model). The model was fitted with the 'glmmTMB' procedure in R ver. 4.0.5 (www.r-project.org). The final output of the model is thus a function indicating the proportion of observations that are expected at a cell in each calendar date. However, we were interested in assessing the onset date of bird migration. This is possible by inverting this model, i.e. by estimating from the fitted function the calendar date at which a given proportion of records is expected. Further details on the procedure for model inversion are provided in the Supporting information.

Most of the 23 investigated species are present in Italy all year round, as the country is both a wintering ground for species that breed further north or northeast (e.g. in Russia) and a breeding ground for species that winter further south (e.g. in North Africa). There are a few exceptions: the ruff *Calidris pugnax*, the Jack snipe *Lymnocryptes minimus*, the common snipe *Gallinago gallinago*, the pintail *Anas acuta*, the Eurasian wigeon *Mareca penelope* and the redwing *Turdus iliacus* only winter in Italy, while the common quail *Coturnix coturnix* and the garganey *Spatula querquedula* only breed in the country. However, the method by Ambrosini et al. (2023) can arrange all these different migration patterns and can therefore be applied to both fully and partially migratory birds as well as to wintering and breeding species. To do that, data entered in the model should include an initial period when individuals are stationary. The accumulation of observations during the stationary period should increase approximately at a constant rate, until they deviate at the onset of migration which produces an increase of observations where migrants

Table 1. Minimum dates (1 January = 1) for pre-breeding migration and their corresponding 10-day periods for 23 game bird species, as determined from our analysis of www.Ornitho.it data and from the European African Bird Migration Atlas (Atlas) (Bairlein et al. 2022, Spina et al. 2022) data (when 5% of individuals are expected to be on migration). For each species, 10-day periods of the end of post-breeding migration obtained from our analyses based on www.Ornitho.it data (when 5% of individuals are expected to still be migrating), along with the wintering phenology, the www.Ornitho.it sample size and the time coverage of the www.Ornitho.it data used are also included. The www.Ornitho.it sample size varies depending on the combination of parameters used when running the model. The 10-day period of pre-breeding migration onset defined in the KCD for Italy is also reported. *from the 2025 KCD update for Italy

Species		This study (Ornitho.it data)					EURING Atlas	KCD
Scientific name	Common name	Pre-breeding migration minimum date	Pre-breeding migration 10-day period	Sample size for pre-breeding migration	Time span used	Wintering phenology	Pre-breeding migration minimum date	Pre-breeding 10-day period for Italy
Spatula querquedula	Garganey	40	FEB 1	81 237–81 259	2000–2023	early	32	FEB 1
Spatula clypeata	Northern shoveler	18	JAN 2	161 308–183 092	2000–2023	interm.	24	FEB 1
Mareca strepera	Gadwall	12	JAN 2	75 289–93 790	2000–2023	interm.	20	JAN 3
Mareca penelope	Eurasian wigeon	12	JAN 2	102 951–110 724	2000–2023	interm.	16	FEB 3
Anas platyrhynchos	Mallard	5	JAN 1	1 058 781–1 126 368	2000–2023	early	7	JAN 1
Anas acuta	Northern pintail	17	JAN 2	30 960–32 781	2000–2023	interm.	19	JAN 3
Anas crecca	Eurasian teal	11	JAN 2	26 622–28 628	2000–2009	interm.	16	JAN 3*
Aythya ferina	Common pochard	12	JAN 2	189 108–202 485	2000–2023	interm.	20	FEB 1
Aythya fuligula	Tufted duck	26	JAN 3	119 003–142 282	2000–2023	late	34	FEB 1
Coturnix coturnix	Common quail	71	MAR 2	3975–3979	2000–2023	early	53	APR 2
Columba palumbus	Common wood pigeon	20	JAN 2	520 798–558 073	2000–2023	interm.	25	FEB 3
Fulica atra	Eurasian coot	15	JAN 2	703 098–748 169	2000–2023	interm.	18	JAN 3
Vanellus vanellus	Northern lapwing	6	JAN 1	453 911–488 983	2000–2023	interm.	19	FEB 1
Lymnocryptes minimus	Jack snipe	26	JAN 3	710–749	2000–2023	interm.	25	FEB 1
Scolopax rusticola	Eurasian woodcock	14	JAN 2	1217–1394	2000–2023	interm.	–2	JAN 2
Gallinago gallinago	Common snipe	0	DEC 3	47 145–49 583	2000–2023	early	5	FEB 1
Tringa totanus	Common redshank	8	JAN 1	25 221–26 402	2000–2023	early	25	FEB 3
Calidris pugnax	Ruff	49	FEB 2	19 548–19 836	2000–2010	early	36	JAN 3
Alauda arvensis	Eurasian skylark	6	JAN 1	11 947–13 170	2000–2011	early	19	FEB 3
Turdus philomelos	Song thrush	0	DEC 3	49 703–51 073	2000–2023	early	8	JAN 2*
Turdus iliacus	Redwing	11	JAN 2	12 483–14 517	2000–2023	interm.	17	JAN 3*
Turdus merula	Eurasian blackbird	9	JAN 1	437 474–456 075	2000–2023	early	40	JAN 2
Turdus pilaris	Fieldfare	10	JAN 1	106 663–116 650	2000–2023	interm.	17	JAN 2*

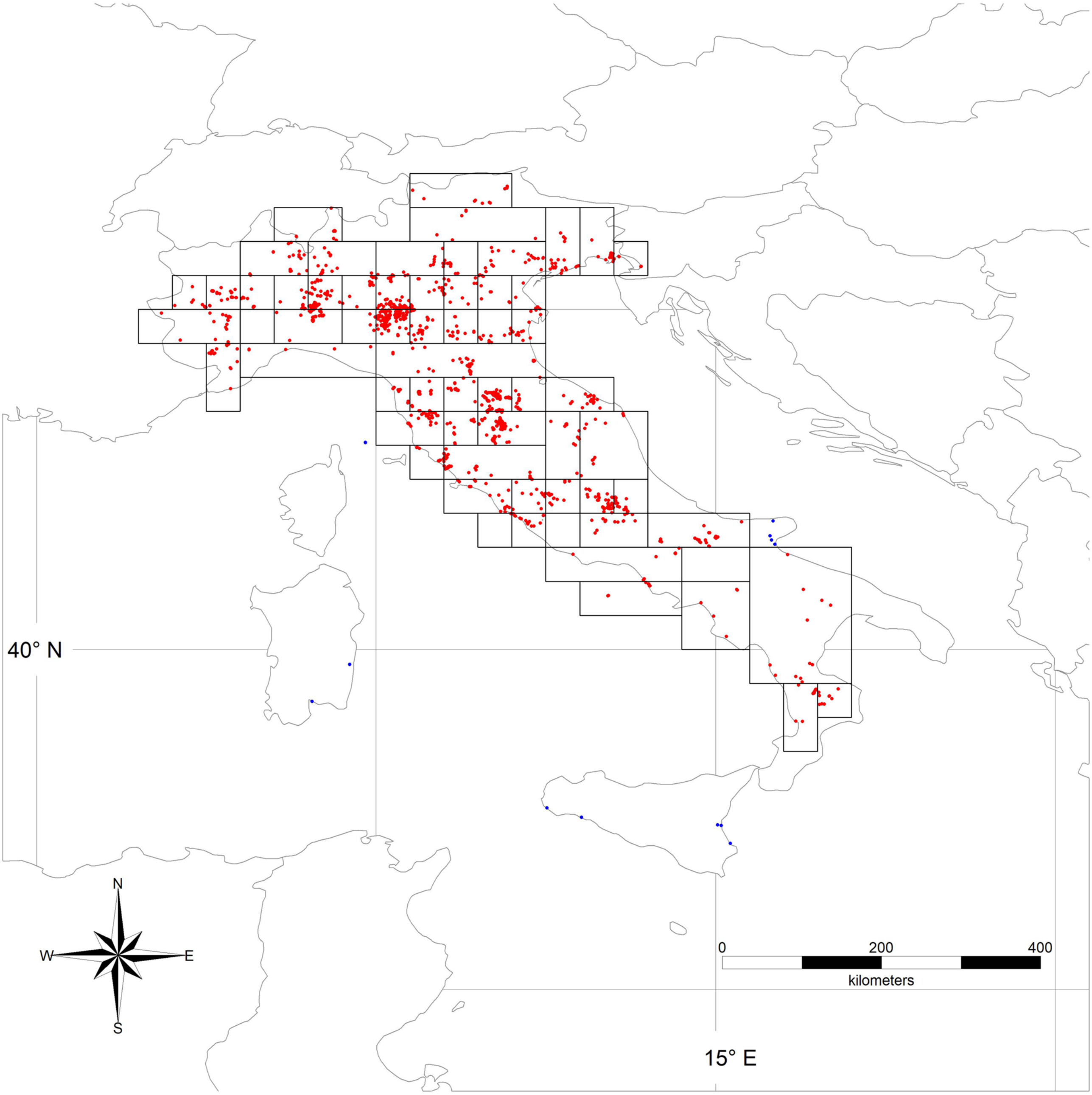

Figure 1. Example of the outcome of the cell merging process for the Eurasian skylark *Alauda arvensis*. Red dots indicate the observations included in the analysis. Blue dots indicate discarded observations.

arrive at that cell, or a decrease in those cells where individuals leave the cell (Fig. 2).

The procedure briefly described above and reported in full detail in the Supporting information thus returns the date when a given proportion of observations is estimated at each cell after considering the observations expected from birds that are stationary in the cell, if any. These values were then spatially interpolated using a grid with 0.5° × 0.5° (latitude x longitude) cells, the inverse distance weighting algorithm, with weights calculated using the Shepard method (Shepard 1968), and a leave-one-out validation routine to choose the best power function for interpolation. Finally, the resulting interpolated map was downscaled to obtain the expected values at cells of 0.1 × 0.1° of size (latitude × longitude, approximately corresponding to 10 × 8 km) using the bilinear method. Since this procedure included a predefined set of parameters with arbitrarily selected values, we selected alternative values for these parameters and re-run the analyses using all 27 possible combinations (see the Supporting information for an overview of these parameters, their meanings, and the different values used). This produced 27 final maps per species, for each predicted proportion of arrived

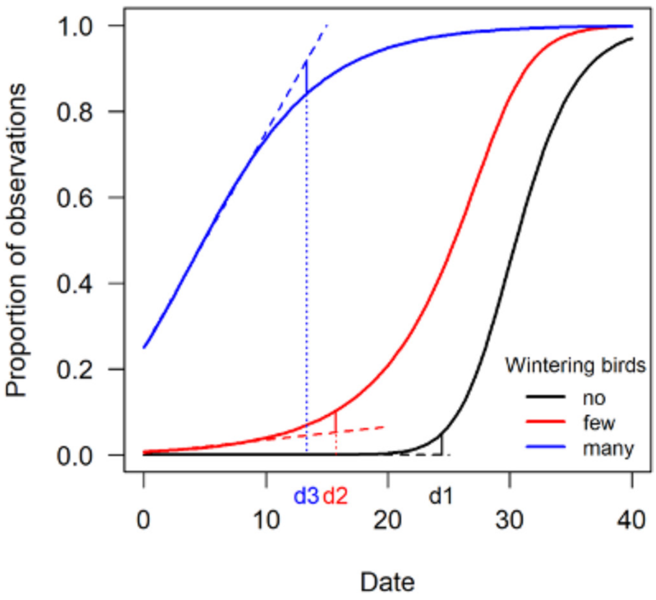

Figure 2. Example curves showing the cumulative proportion of observations within a grid cell for three migratory strategies: a fully migratory species that does not winter in the study area, a partial migrant with some individuals wintering locally and others migrating, and a wintering species that leaves the area to migrate. Dashed lines indicate the initial linear increase attributed to local individuals; d1, d2 and d3 mark the dates at which each curve deviates by 5% from linearity, used here as a conservative estimate of migration onset.

migrants (i.e. PRED values as outlined in the Supporting information) which were then averaged. A map delineating the sensitivity of predictions under different arbitrary choices of the parameters for each cell was also produced following Ambrosini et al. (2023) with the formula

$$\text{Sensitivity} = \frac{1}{26}\sum_{i=1}^{27}\left(d_i - \bar{d}\right)^2$$

where d_i is the data estimated at that cell from the model with the i-th combination of parameter values and $\bar{d}$ their mean value, i.e.

$$\bar{d} = \frac{1}{27}\sum_{i=1}^{27} d_i$$

It is important to note that the selection of the first day-of-the-year for analysis depended on the timing of the annual life cycle of each species, as this should be in a period when individuals are reasonably stationary in their wintering grounds. We categorized species into three groups based on their wintering phenology as described by Cramp (1988) (see details in the Supporting information). However, for the common blackbird *Turdus merula*, we used data from Andreotti et al. (2010), as Cramp's (1988) assessment of the species' wintering phenology was found to be inaccurate for Italy. Likewise, for the Eurasian woodcock *Scolopax rusticola*, we based our classification on data from Aradis et al. (2006), which involved regular 10-day interval monitoring, as this species shows potential for late arrival from post-breeding migration in Italy. Our categories thus correspond to species with different wintering phenologies: 'early' (species that become stationary in their wintering grounds at the beginning of December), 'intermediate' (stationary in their wintering grounds from mid-December) and 'late' (stationary in their wintering grounds from the beginning of January). We checked whether the species wintering phenology affected our results by comparing the pre-breeding migration onset date we estimated between these groups (full details of this analysis are reported in the Supporting information). No differences would indicate that our method estimated the date of pre-breeding migration onset independently of this model parameter.

The www.Ornitho.it databank allows users to record the observation of multiple individuals, which may result in records of over a thousand individuals per observation. It was thus crucial to assess whether a substantial number of individuals observed in a single day may bias the results. Indeed, in such a case the cumulative proportions at a cell – which are central in the analysis – rise abruptly, for example transitioning from 0 to 1000 in a single day. Clearly, this can affect the parameters of the interpolated model and, consequently, the predicted date of migration onset. We thus investigated the potential effects of the simultaneous records of many birds on two species with distinct migration strategies: the Eurasian teal *Anas crecca* and the song thrush *Turdus philomelos*. The Eurasian teal typically forms large aggregations in water bodies, while song thrushes gather to a lesser extent during migration. To assess the effects of simultaneous records of many birds, we applied different limits on the maximum number of individuals per record for these species and compared the results. Full details of the methods and results of this preliminary investigation are reported in the Supporting information. Briefly, the results showed that the arbitrary choice of a maximum number of individuals per observation has a limited effect on the estimated minimum onset date of pre-breeding migration in these species. Indeed, the variations in the estimated starting dates were, at most, 2 days. We therefore included a maximum value of 100 individuals per observation for the analyses of all species. In practice, whenever the number of observed individuals entered in one record of the Ornitho.it databank was larger than 100, it was set to 100, and all the following analyses were run on this modified dataset.

Post-breeding migration timing

For the post-breeding migration timing analysis we adopted the same procedure used to model pre-breeding migration with the main difference that, for post-breeding migration, calendar dates were calculated backwards starting from the period when individuals are stationary (i.e. 30 November for species with early wintering phenology, 14 December for species with intermediate wintering phenology and 31 December for species with late wintering phenology) (Ambrosini et al. 2014, 2023). Cumulated proportions were then calculated backwards in time towards the breeding season until 1 July. Thus, for post-breeding migration, the procedure returns the dates after which a given proportion of individuals is encountered, and the maps indicate the end-tail of migration.

Additionally, to further validate our assessment of stationary periods, we tested whether the estimated post-breeding migration end date differed among the species belonging to the three wintering phenology groups (full details of this procedure are reported in the Supporting information). Importantly, in this case, a significant difference would indicate that the stationary periods were correctly defined, as they reflect the species' wintering phenology, that is, the end of post-breeding migration (see the Supporting information for further details).

Estimation of pre- and post-breeding migration dates

We conservatively defined the onset of pre-breeding migration as the date by which 5% of migratory individuals have been observed. The final output of our analysis consists of 23 maps – one for each species – showing the migration onset date across Italy. These maps are reported in the Supporting information. The online data repository associated with this paper also provides maps corresponding to different proportions of observations (0, 1, 10 and 50%), along with all the other maps produced during the intermediate steps of the analysis. For brevity, we present in the main text the maps of the eleven species that displayed a discrepancy of two or more 10-day periods between our estimated onset dates and those reported by the KCD (see below for further details on the comparison).

To determine the earliest pre-breeding migration dates of each species in Italy, we began by clipping the raster map derived from www.Ornitho.it data to the extent of Italy. This clipping was performed to exclude sea areas, focusing solely on mainland Italy and its islands. We then used the Python 'numpy' module to extract the minimum value from this raster, representing the earliest onset date of pre-breeding migration as in Bairlein et al. (2022).

For post-breeding migration, a similar process was followed. We clipped the raster map showing the date when 5% of individuals are expected to still be migrating, again removing sea areas. However, in this case, we extracted the maximum value from the raster, indicating the latest date of post-breeding migration. We then converted these dates from the maps generated in this paper into the corresponding 10-day period. To evaluate the uncertainty of both pre- and post-breeding migration maps, we clipped the respective standard error maps, again removing sea areas, and extracted the maximum values over Italy.

Comparison of results with other phenology estimates

We extracted data on pre-breeding migration onset from the scientific report 'Timing of migration of huntable species' (Bairlein et al. 2022), available in the Eurasian African Bird Migration Atlas (Spina et al. 2022), hereafter simply the 'Atlas'. This report applied the same analytical method used in this study to the ringing data from the EURING databank. It also provided maps of pre-breeding migration timing for 57 game species at a European scale, specifically when 5% of individuals are expected to begin migrating. From these maps, we identified the onset date of pre-breeding migration in Italy for the 23 species included in this study. The procedure followed was as outlined earlier in the 'Estimation of pre- and post-breeding migration dates' section for pre-breeding migration with www.Ornitho.it data. Then, we compared the pre-breeding migration onset dates derived from www.Ornitho.it data with those from the Atlas using ANOVA-based repeatability analysis (Nakagawa and Schielzeth 2010). Repeatable results would support the reliability of our estimates, as they would be consistent with those obtained from an entirely different dataset.

Additionally, we compared the estimated 10-day periods of pre-breeding migration onset from our study with those reported for Italy in the latest KCD, given the pivot role this document plays in determining the timing of the hunting season in EU countries.

Results

Timing of pre-breeding migration

Pre-breeding migration onset dates (when 5% of individuals are expected to be on migration) ranged from 31 December (common snipe and song thrush) to 11 March (common quail) (Table 1). The maximum standard error of all 23 game species ranged from 1.6 (ruff) to 6.5 days (mallard *Anas platyrhynchos*) across Italy. Furthermore, Fig. 3, 4 and the Supporting information show that pre-breeding migration onset obtained from www.Ornitho.it data was heterogenous across the 23 game species we analysed. Finally, our choice of date to start accumulating observations, based on the wintering phenology of each species did not affect the estimated onset dates of pre-breeding migration ($F_{2,20} = 0.49$, $p = 0.62$; see the Supporting information for further details).

Timing of post-breeding migration

End dates of post-breeding migration (i.e. when 95% of individuals have already been recorded and 5% are expected to still be migrating) were less heterogenous than those of pre-breeding migration onset (Fig. 5, 6, Supporting information). They ranged from 10 October (garganey) to 4 December (tufted duck *Aythya fuligula*). The maximum standard error of these maps for all 23 game species ranged from 0.68 (Jack snipe) to 5.24 days (Eurasian coot *Fulica atra*) across Italy. The estimated end date of post-breeding migration differed significantly between the wintering phenology groups ($F_{2,20} = 18.4$, $p < 0.001$) with species in the early group showing end dates of autumn migration significantly earlier than those in the intermediate and late groups (see the Supporting information for further details).

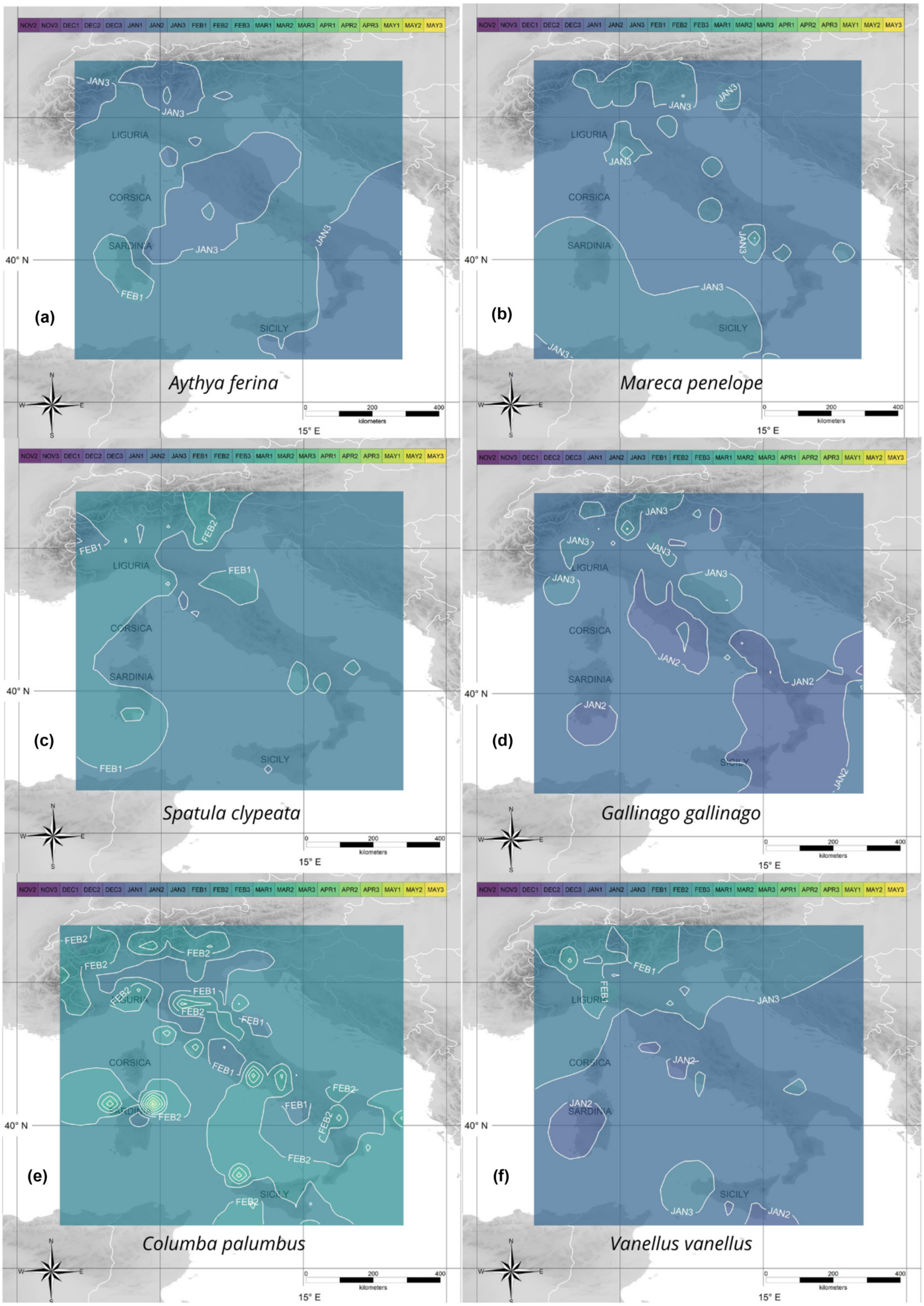

Figure 3. (a), (b), (c), (d), (e) and (f) onset of pre-breeding migration of six species, which displayed a discrepancy of two or more 10-day periods between the pre-breeding migration onset reported by the KCD and those derived from www.Ornitho.it data. Dates indicate when 5% of observed individuals are expected to be on migration. Isolines represent regions where the migration date is the same. For example, in map (a) of the common pochard *Aythya ferina*, in the south-eastern part of Sicily, the pre-breeding migration onset date is during the second ten days of January, whereas in the rest of the island, it is primarily during the last ten days of January. The months are divided into 10-day periods, as defined in the EU Birds Directive Key Concepts Document (e.g. JAN1, JAN2, JAN3). The labels on isolines indicate the first day of each 10-day period, so JAN1 means 'January 1', JAN2 means 'January 11', and JAN3 means 'January 21', and so forth.

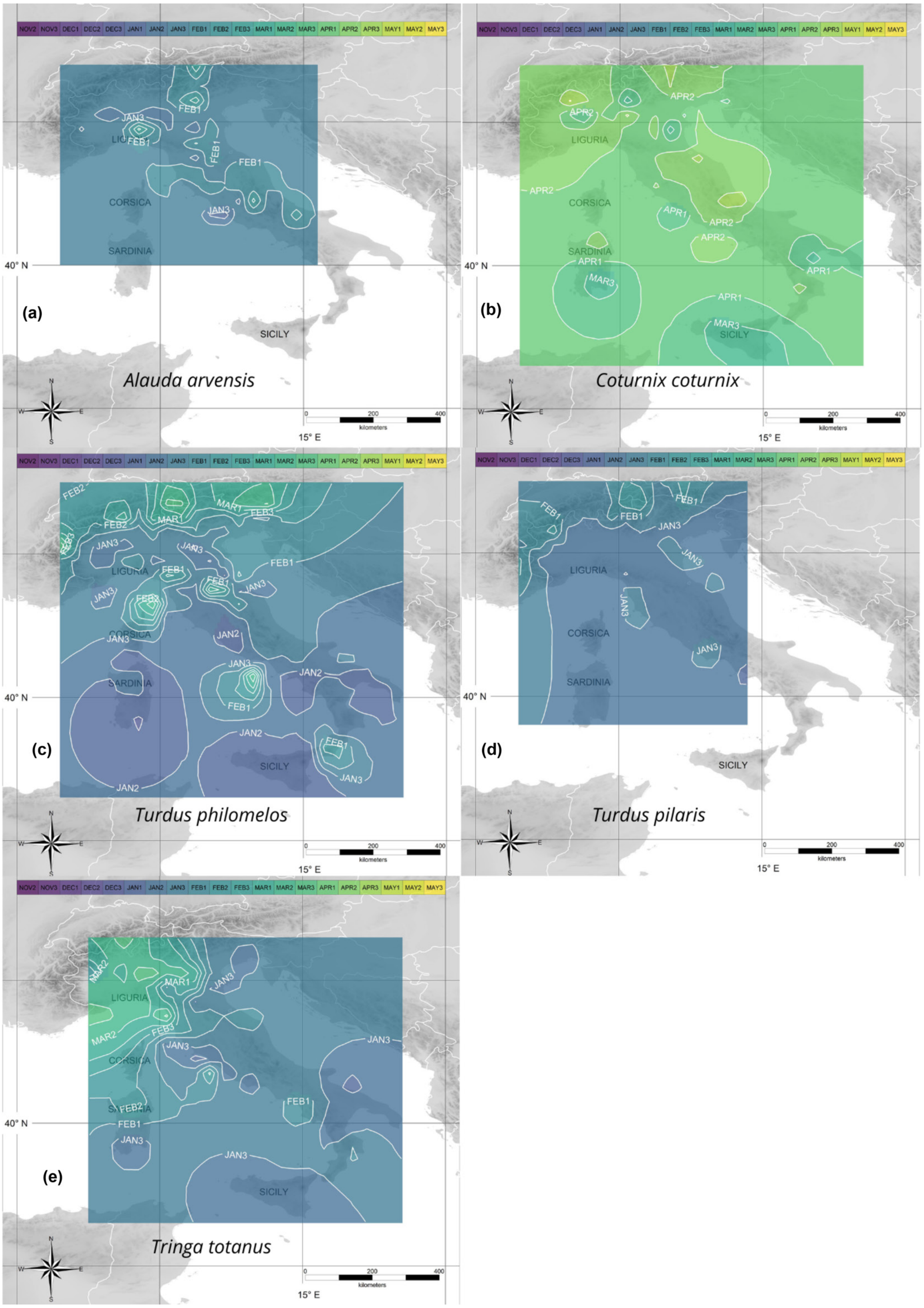

Figure 4. (a), (b), (c), (d) and (e) onset of pre-breeding migration of five species, which displayed a discrepancy of two or more 10-day periods between the pre-breeding migration onset reported by the KCD and those derived from www.Ornitho.it data. Dates indicate when 5% of observed individuals are expected to be on migration. Isolines represent regions where the migration date is the same. For example, in map (b) of the common quail *Coturnix coturnix*, in the south-eastern part of Sardinia, the pre-breeding migration onset date is during the second ten days of March, whereas in the rest of the southern part of the island, it is primarily during the first ten days of March. The months are divided into 10-day periods, or 'decades', as defined in the EU Birds Directive Key Concepts Document (e.g. JAN1, JAN2, JAN3). The labels on isolines indicate the first day of each decade, so JAN1 means 'January 1', JAN2 means 'January 11', and JAN3 means 'January 21', and so forth.

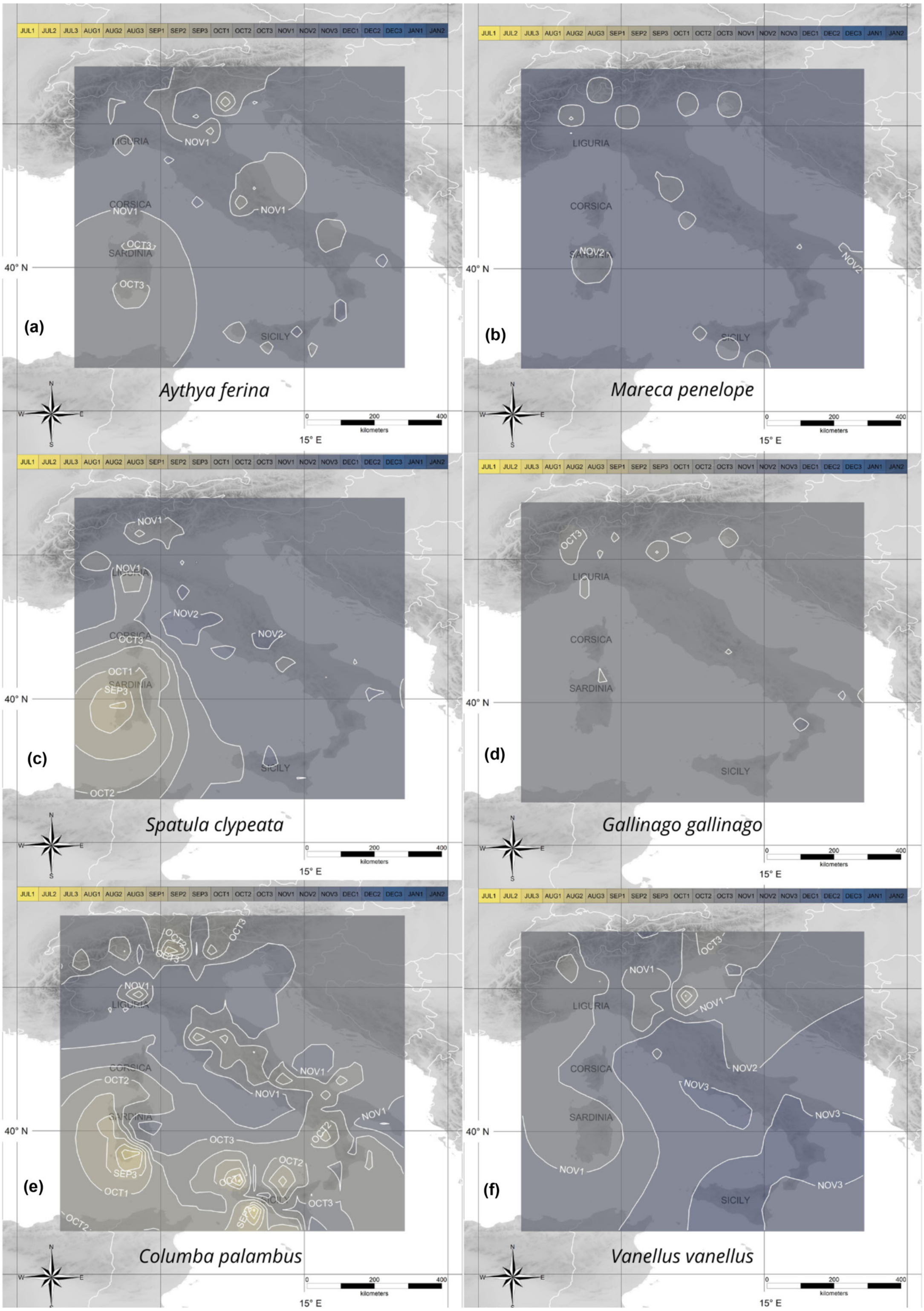

Figure 5. (a), (b), (c), (d), (e) and (f) end of post-breeding migration of six species, which displayed a discrepancy of two or more 10-day periods between the pre-breeding migration onset reported by the KCD and those derived from www.Ornitho.it data. Dates indicate when 5% of individuals are expected to still be migrating. Isolines indicate regions where the average migration date is the same. For example, in map (a) of the common pochard *Aythya ferina* in the southern tip of Sardinia, the post-breeding migration end date occurs during the second ten days of October. The months are divided into 10-day periods, according to the EU Birds Directive Key Concepts Document (e.g. OCT1, OCT2, OCT3). The labels on isolines correspond to the first day of each 10-day period, so OCT1 means 'October 1', OCT2 means 'October 11', and OCT3 means 'October 21', and so forth.

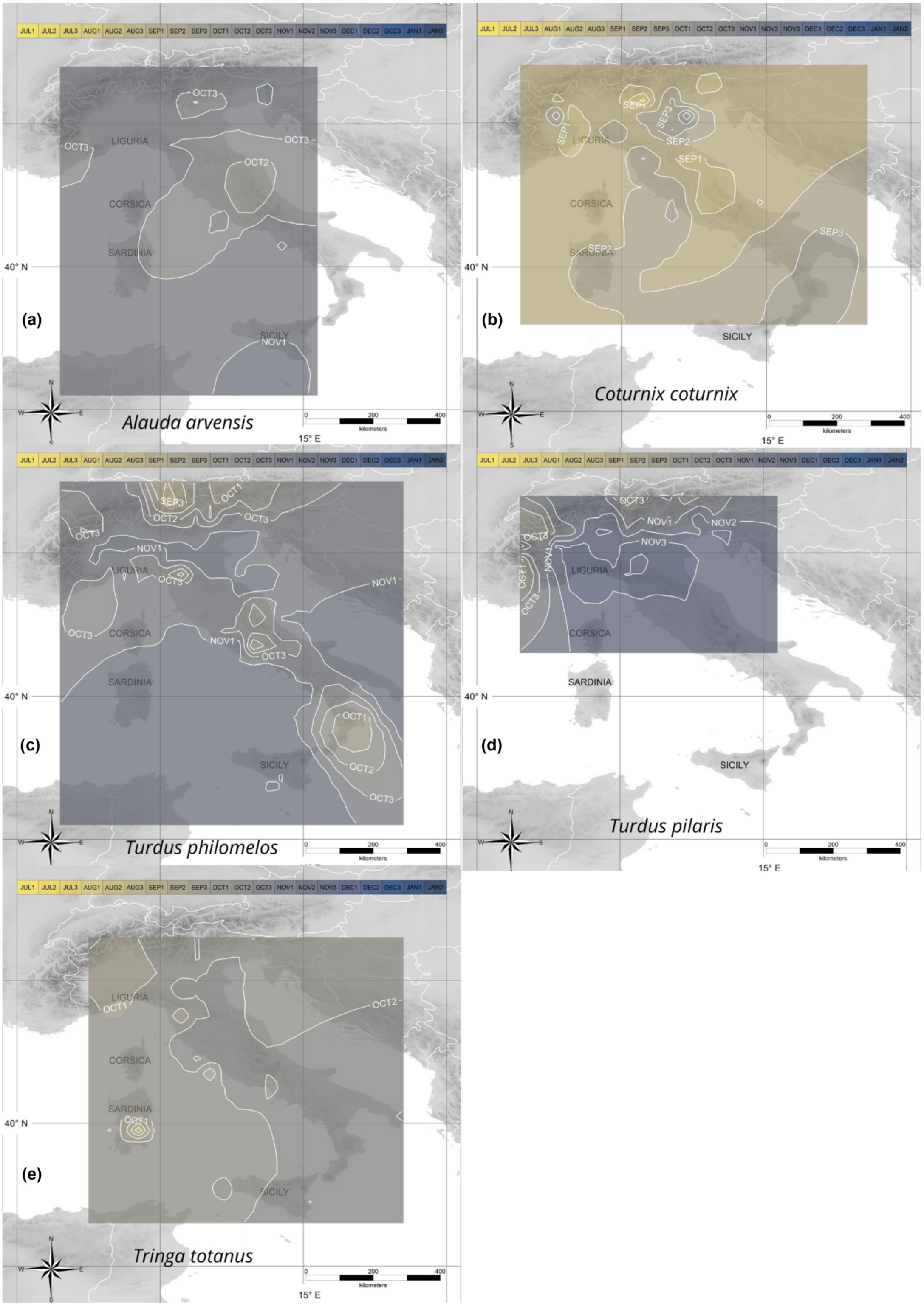

Figure 6. (a), (b), (c), (d) and (e) end of post-breeding migration of five species, which displayed a discrepancy of two or more 10-day periods between the pre-breeding migration onset reported by the KCD and those derived from www.Ornitho.it data. Dates indicate when 5% of individuals are expected to still be migrating. Isolines indicate regions where the average migration date is the same. For example, in map (a) the post-breeding migration end date of the skylark *Alauda arvensis* in the central-southern part of Sicily occurs during the first ten days of November. The months are divided into 10-day periods, known as 'decades', according to the EU Birds Directive Key Concepts Document (e.g. OCT1, OCT2, OCT3). The labels on isolines correspond to the first day of each decade, so OCT1 means 'October 1', OCT2 means 'October 11', and OCT3 means 'October 21', and so forth.

Comparison with the EURING Atlas

The dates of pre-breeding migration onset derived from the Atlas ranged from 29 December (Eurasian woodcock) to 22 February (common quail). Migration onset dates from www.Ornitho.it data and those obtained from the Atlas were repeatable (repeatability = 0.703, $F_{2,22} = 5.73$, $p < 0.0001$; Fig. 7).

The common blackbird exhibited the greatest discrepancy, with a 31-day difference between the migration onset dates estimated from Ornitho.it data and those from the Atlas. In contrast, the Jack snipe displayed only a two-day difference between the two data sources.

Comparison with the KCD

Overall, our study's estimates of the 10-day period of pre-breeding migration onset differed from the KCD for 20 species (87%) (Table 1). Among these, 11 species (48%) had an estimated onset of pre-breeding migration that in our analyses was at least 20 days earlier than indicated in the KCD. Only one species, the ruff, exhibited a pre-breeding migration timing that was 20 days later than indicated in the KCD (FEB2 versus JAN3). The common redshank *Tringa totanus* and the Eurasian skylark showed the biggest discrepancy between our findings and the KCD: our results indicated that these species begin their pre-breeding migration approximately 50 days earlier than estimated in the KCD (JAN1 in our analysis versus FEB3 in the KCD; Table 1). Following closely were the common snipe, the common wood pigeon *Columba palumbus* and the Eurasian wigeon, with our findings showing their pre-breeding migration onset approximately 40 days earlier than indicated by the KCD (for the common snipe DEC3 versus FEB1; for the common wood pigeon and the Eurasian wigeon the JAN2 versus FEB3). The northern lapwing *Vanellus vanellus* and the common quail also showed a big discrepancy, with our results showing a pre-breeding migration onset one month earlier than stated by the KCD (for the northern lapwing JAN1 versus FEB1; for the common quail MAR2 versus APR2). The three species with the same 10-day period of pre-breeding migration onset as reported in the KCD were the Eurasian woodcock (JAN2), the garganey (FEB1) and the mallard (JAN 1; Table 1, Supporting information).

Discussion

We estimated the timing of pre- and post-breeding migration for 23 game birds based on citizen science data. Our analysis revealed that the onset of pre-breeding migration closely matched the timing reported in the Atlas based on ringing data. Additionally, we compared our pre-breeding migration results with the specific 10-day period outlined in the KCD for Italy and showed that for 19 species (83%) our analysis indicated an earlier pre-breeding timing than what was reported in the KCD.

One potential bias in our analysis is that the migration onset date we obtained depends on the date when we start accumulating observations (Supporting information). The estimated post-breeding migration end dates differed significantly among species from different wintering phenology groups. This supports the validity of our stationary period definitions, as they reflect the species' end of post-breeding

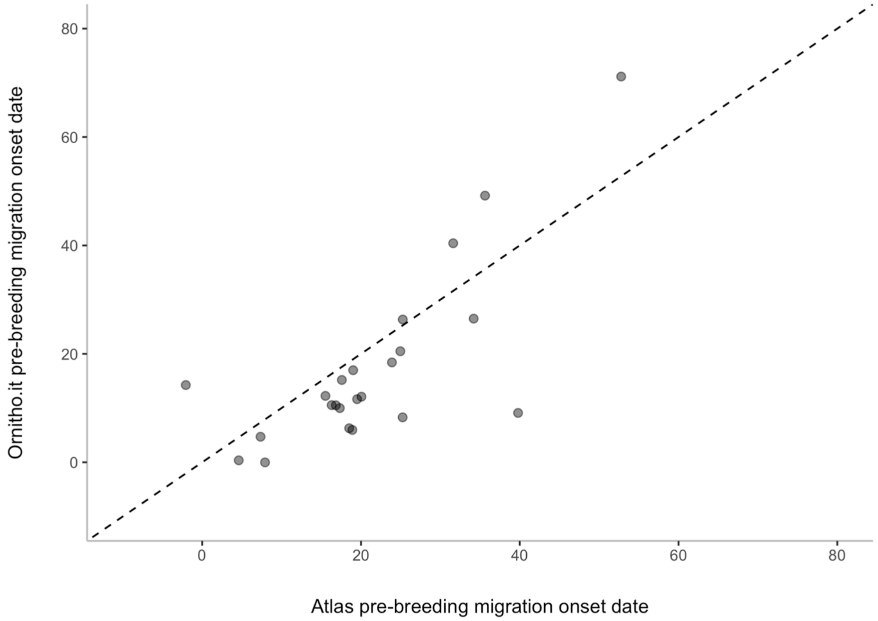

Figure 7. The onset dates of pre-breeding migration derived from our analyses with www.Ornitho.it (when 5% of individuals are expected to be on migration) is plotted against the onset dates of pre-breeding migration from the European African Bird Migration Atlas, based on ringing data (when 5% of individuals are expected to be on migration). Only the 23 species analysed from both data sources are represented (see Table 1 for the list of species). Dates are reported as days from 1 January (1 January = 1). The dashed line represents the 1:1 relationship.

migration. Moreover, we showed there was no significant effect on the onset date of pre-breeding migration (Supporting information). This indicates that the estimated 10-day period of pre-breeding migration onset was not affected by the wintering phenology group in which we divided our species. Consequently, our migration onset maps are mostly based on information present in the data, rather than prior assumptions used to parameterize the models. Indeed, the procedure effectively provided early or late pre-breeding migration onset dates regardless of when we started accumulating observations. Therefore, while the starting date of the model determines the date from which we started accruing observations, the model still captures a biological pattern because some species with early wintering phenology leave later during pre-breeding migration.

Figure 3, 4 and the Supporting information show that pre-breeding migration timing is heterogenous across the 23 species we studied. Overall, the maps show that the onset of pre-breeding migration occurs progressively later in northern areas. In addition, we can observe that some species appear to migrate from northern Africa through Sardinia and Corsica, as already described for the song thrush (Andreotti et al. 1999). This migratory corridor is evident in the map of the northern shoveler *Spatula clypeata* (Fig. 3c), the song thrush (Fig. 4c), the common quail (Fig. 4b), and the Eurasian coot (Supporting information). It is also present in the maps of the common redshank (Fig. 4e), and the common blackbird (Supporting information), where the migratory corridor seems to continue up to Liguria (north-western Italy). Figure 5, 6 and the Supporting information show that post-breeding migration timing progressively shifts as birds move southwards. Indeed, in the post-breeding maps, southern areas show a later end of migratory movements. These southward movements are absent from the pre-breeding migration maps, which showed the opposite pattern, indicating that late southward movements during post-breeding migration do not affect the estimate of pre-breeding migration onset.

Comparison with the EURING Atlas

The onset dates of pre-breeding migration obtained with our analysis using citizen science data is significantly and positively related to those estimated from the Atlas ringing data. The consistent results from two different datasets regarding pre-breeding migration timing demonstrate the robustness of these findings and of the analytical method. Much of our understanding of migration comes from ring recoveries and this data provided invaluable insights into many aspects of migratory behaviour (Thorup et al. 2014, 2017, Marx et al. 2016, Musitelli et al. 2019, Roberts et al. 2023). However, ring recoveries can be highly biased due to uneven distribution of ringing and recapture efforts, which are limited to particular areas and may be susceptible to changes in migration patterns or local weather conditions (Thorup and Conn 2009). On the other hand, citizen science data is more widespread. Thanks to a vast network of observers, millions of observational reports are collected across extensive areas year-round, creating a vast amount of information. However, also citizen science data have some spatial and temporal limitations, because observers select when and where they want to record species (Johnston et al. 2023). This variability in human observation effort is unlikely to have significantly distorted our reconstructions of migration timing, given the generally very large sample size available (ranging from several thousand to millions of birds; Table 1). Furthermore, the analytical method used in this study has been shown to be highly robust to spatial biases and large variations in sample size (Ambrosini et al. 2023). Citizen sampling effort is also likely to vary throughout the year, e.g. depending on the weather. However, such biases should be minimized because we accumulated observations across multiple years.

The onset dates of pre-breeding migration derived from citizen science data are slightly earlier than those derived from ringing data for most species (Fig. 7). Ringing records span a multi-decadal time series, with the earliest Italian record in the Atlas dating back to 1929, whereas most citizen science observations have been collected only within the past two decades (Table 1). Therefore, citizen science data may indicate an earlier onset of pre-breeding migration, likely due to climate change, which remains undetected in ringing data because they are aggregated over longer periods (Stervander et al. 2005, Thorup et al. 2007, Romano et al. 2023).

Among the 23 species, the common blackbird showed the largest difference (31 days). Given the large sample size in both datasets (with over 40 000 observations each in our analysis and the ringing data), this discrepancy is unlikely to be due to sampling limitations. A potential bias in the ringing data of the common blackbird originates from the closure date of the hunting season in Italy. In 1967, the hunting season was closed on 10 January (Regio Decreto 1016/1939 modified by Law 799/1967), and from 1977 onwards, on 31 December (Italian Law 968/1977). Additionally, ringing station activity has been very limited in January, due to the tradition of ringing birds during peak migratory periods. Consequently, a low number of ring recoveries is expected in January, which may explain why ringing data indicated a much later phenology than citizen science data.

Comparison with KCD

Out of the 23 species studied, 19 (83%) start pre-breeding migration later according to the KCD compared to our findings. These species show a close match between the pre-breeding migration onset derived from www.Ornitho.it data and that derived from the Atlas. This suggests a strong biological pattern reflected by both data sources, indicating that for certain species the pre-breeding migration 10-day periods reported in the KCD for Italy were based on limited data (Andreotti et al. 2023).

According to the KCD, two species, the common redshank and the Eurasian skylark, start pre-breeding migration more than one month and a half (five 10-day periods) later than indicated by our results and three or four 10-day periods later compared to the Atlas, respectively. Both species can be hunted in Italy, being listed in Annex II - Part B of the Birds Directive

2009/147/EC. However, under the national hunting law 157/1992, the common redshank is protected, and the Eurasian skylark can only be hunted until 31 December. Even though now there is no conflict with the Bird Directive, due to these hunting limitations, our results suggest that the 10-day periods indicated in the KCD for these species should be revised.

In addition, our findings indicate that the common snipe and the Eurasian wigeon start pre-breeding migration in DEC3 and in JAN2, respectively, and these timings are both about 40 days before what the KCD indicates (FEB1 and FEB3, respectively). In Italy, the current hunting season for these species, as specified by the national hunting law, lasts until 31 January. According to our results, this period overlaps with their pre-breeding migration. The fact that different data sources, ringing and citizen science, produce similar estimates for the onset of pre-breeding migration, suggests the need to revise the KCD and adjust the hunting period accordingly. This would ensure compliance with the Birds Directive for these species, as well as for others with smaller discrepancies. Conversely, the discrepancy between the observational data (18 February corresponding to FEB2), the Atlas (5 February) and the KCD (JAN3) on the pre-breeding migration onset of the Ruff can be attributed to the extensive decline of this species' European population in recent decades (Burfield et al. 2023). Indeed, the large decrease of the population breeding in south-western Europe and Fennoscandia might have led to a shift and contraction of the migratory season.

For a few species, our results can also be compared with data obtained from telemetry. To our knowledge, the onset of pre-breeding migration in Italy has been calculated by telemetry data only for the Eurasian teal (Giunchi et al. 2019), the Eurasian woodcock (Tedeschi et al. 2020) and the fieldfare *Turdus pilaris* (McKinlay et al. 2024). While the study on the Eurasian teal was not designed to determine the earliest onset of pre-breeding migration, the results presented in Giunchi et al. (2019) align with the migration timing obtained in this study. In contrast, the results of the other two studies show discrepancies, with 30 and 56 days for the Eurasian woodcock and the fieldfare, respectively. As highlighted in the Introduction, these discrepancies might be attributed to methodological biases, such as small sample sizes that may not be representative of the population, the failure to sample earlier migrants by age and sex, and unassessed tag effects on bird body condition and behaviour, all of which could hinder the identification of migration onset.

In summary, this study shows that citizen science data from the Ornitho.it dataset provide reliable migration timing results of game birds in Italy. It also highlights the importance of using multiple methods to calculate migration timing, especially for hunted species that require well-informed, evidence-based management plans for their conservation. By combining different data sources, studies on migration timing can minimize biases of each data type and provide critical information for the effective management of game species. This integrative approach aligns with the methodological recommendations of the European Commission to Member States for determining the onset of pre-breeding migration (Andreotti et al. 2023).

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Author contributions

Susan McKinlay: Data curation (equal); Formal analysis (equal); Investigation (equal); Visualization (equal); Writing – original draft (lead); Writing – review and editing (equal). **Alessandra Costanzo**: Investigation (equal); Writing – review and editing (equal). **Claudio Celada**: Funding acquisition (equal); Writing – review and editing (equal). **Marco Gustin**: Funding acquisition (equal); Writing – review and editing (equal). **Alessandro Andreotti**: Writing – review and editing (equal). **Lorenzo Serra**: Writing – review and editing (equal). **Simona Imperio**: Writing – review and editing (equal). **Stephen Baillie**: Writing – review and editing (equal). **Franz Bairlein**: Writing – review and editing (equal). **Fernando Spina**: Writing – review and editing (equal). **Roberto Ambrosini**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Supervision (equal); Visualization (equal); Writing – review and editing (equal).

Transparent peer review

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.fxpnvx14z (McKinlay et al. 2025).

Supporting informatio

The Supporting information associated with this article is available with the online version.

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