Bird Study

ISSN: 0006-3657 (Print) 1944-6705 (Online) Journal homepage: https://www.tandfonline.com/loi/tbis20

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To cite this article: Samuele Ramellini, Andrea Simoncini, Gentile Francesco Ficetola & Mattia Falaschi (2019) Modelling the potential spread of the Red-billed Leiothrix *Leiothrix lutea* in Italy, Bird Study, 66:4, 550-560, DOI: 10.1080/00063657.2020.1732864

To link to this article: https://doi.org/10.1080/00063657.2020.1732864

BIRD STUDY
2019, VOL. 66, NO. 4, 550–560
https://doi.org/10.1080/00063657.2020.1732864

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Modelling the potential spread of the Red-billed Leiothrix *Leiothrix lutea* in Italy

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ABSTRACT
Capsule: The introduced Red-billed Leiothrix *Leiothrix lutea* can greatly expand its range in Italy, with many regions being at high risk of invasion due to their high habitat suitability.
Aims: To assess the environmental variables affecting the distribution of the Red-billed Leiothrix during the invasion process, and to predict the potential distribution of the species in Italy.
Methods: We retrieved data on 548 occurrences from Liguria (northern Italy), Tuscany, and Latium (Central Italy) using the Ornitho.it portal, a citizen science-based resource. We used species distribution models to assess the most important climatic and landscape variables for the presence of the species and to generate a countrywide habitat suitability map.
Results: Red-billed Leiothrix distribution was jointly affected by climatic and landscape variables, being related to precipitation seasonality, percentage cover of agricultural areas, and annual precipitation. Habitat suitability for the species was highest at intermediate levels of precipitation seasonality, decreased with the amount of agricultural areas, and increased with annual precipitation. The results of species distribution models were highly consistent across regions. The areas with the highest suitability for the species occurred in a strip spanning the northern and western sides of Italy, particularly in regions with a Mediterranean climate.
Conclusion: Broad areas of Italy have a high risk of invasion by the Red-billed Leiothrix. We provide fine-grained information on the magnitude of habitat suitability over the Italian peninsula.

ARTICLE HISTORY
Received 6 August 2019
Accepted 20 December 2019

Invasive alien species have major negative impacts on native communities and promote the homogenization of global floras and faunas (Elton 1958, McKinney & Lockwood 1999, Nentwig 2007, Primack & Sher 2018). Moreover, the introduction of invasive alien species influences the economic system of the invaded regions, with often unpredictable outcomes (Pimentel *et al.* 2005). Predicting the spread of alien species is pivotal for their control (Elith 2017). This, in turn, requires knowledge of the factors determining the establishment and expansion of introduced species. Still, knowledge of the future spread and the processes that drive it is lacking for many alien bird species (Engler *et al.* 2017).

This study focuses on the Red-billed Leiothrix *Leiothrix lutea*, a polytypic species belonging to the family of Babblers (*Passeriformes*, *Timaliidae*) with an Indo-Malayan primary distribution range (Collar *et al.* 2017). This Babbler has been frequently released into the wild through the pet trade, one of the main introduction pathways of invasive alien species (Richardson 2010, Pârâu *et al.* 2016). The Red-billed Leiothrix appears to have species-specific ecological and morphological traits that make it a successful invader across many different regions of the world (Pereira *et al.* 2017). It has an important impact on biodiversity and has been classified as one of the seven bird invasive alien species with the strongest effects on native biota (Martin-Albarracin *et al.* 2015), because of competition with native birds and seed dispersion of both native and non-native plant species (Tassin & Rivière 2001). Its presence as a nonindigenous species has been documented in Japan, Hawaii, and Europe (Collar *et al.* 2017). In Europe, the Red-billed Leiothrix has established populations in Spain, Portugal, France, and Italy (Lever 2005, Brichetti & Fracasso 2010, Pereira *et al.* 2020). In Italy, the species is considered a naturalized breeding species (Baccetti *et al.* 2014, Brichetti & Fracasso 2015), and has been recorded mainly in Friuli, Latium, Liguria, Tuscany, and the Venetian regions, with scattered data from other regions (Spanò *et al.* 2000, Puglisi *et al.* 2009, 2011, Ramellini 2017, Pereira *et al.* 2020). In this country, the species has been spreading since 1980 (Brichetti & Fracasso 2010) and many reports have been published on its local expansion dynamics (Verducci 2009, Baghino & Fasano 2017, Ramellini 2017). Knowledge

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Supplemental data for this article can be accessed at https://doi.org/10.1080/00063657.2020.1732864.

on the factors affecting Red-billed Leiothrix distribution is limited to the native range, Japan, Spain, and Hawaii (Fisher & Baldwin 1947, Amano & Eguchi 2002a, Herrando *et al.* 2010, Collar *et al.* 2017), and fine-scale predictions of its potential expansion are currently restricted to the northeastern Iberian Peninsula (Herrando *et al.* 2010, but see also Pereira *et al.* (2020) for a continental-scale analysis). In Italy, no study has provided information on the factors driving Red-billed Leiothrix distribution, nor has provided information on its potential countrywide invasion.

In this study, we aimed to: (i) assess the factors driving Red-billed Leiothrix distribution in Italy, (ii) identify the areas in Italy that suffer the highest invasion risk, by building species distribution models (SDMs, Elith & Leathwick 2009) with occurrence data from Liguria, Tuscany, and Latium. This knowledge will help to set up appropriate monitoring protocols to prevent further invasions by the Red-billed Leiothrix in Italy. Given the current knowledge of the habitat preferences of the species (Herrando *et al.* 2010, Collar *et al.* 2017, Ramellini 2017) and of the factors that generally drive species distribution (Bowman *et al.* 2017, Bradie & Leung 2017), we hypothesized that: (i) SDMs applied to Red-billed Leiothrix would predict an expansion of the species in Italy, and (ii) climatic and vegetation variables (cover of broadleaved forest and shrubs) would play a key role in determining the Red-billed Leiothrix distribution in Italy.

Methods

Sources of data

We extracted presence records of Red-billed Leiothrix at the 1 km^2 resolution from the Ornitho portal (www.ornitho.it). This open-access platform collects georeferenced and validated biodiversity data within Italian national borders and its archives are freely searchable by contributors. We did not consider other portals (e.g. eBird and iNaturalist) as they include a very small volume of data for the study species, compared to Ornitho. The use of datasets from citizen science projects has gained momentum in ecology during the last decades (Kobori *et al.* 2016, Ellwood *et al.* 2017) and has been successfully employed in invasion biology (Gallo & Waitt 2011, Falaschi *et al.* 2018). The research on the Ornitho portal was performed using the following entries: temporal extent 'All the period recorded in the system', species 'Red-billed Leiothrix', spatial extent 'Regions of Latium, Tuscany, and Liguria', i.e. the three regions in Italy where the species is currently widespread. In compliance with the site's rules, data usage permission was requested via personal communication to the users involved. These data were complemented with our own field records, collected in 2012–18 in Latium and Liguria. All data were then combined into our final dataset, consisting of 548 georeferenced records, 228 from Liguria, 230 from Tuscany and 90 from Latium. The distribution of records is shown in Figure 1. We assumed that these records represented individuals that had been in the wild for some time or were within already established populations, i.e. we assumed that no records came from individuals temporarily recorded in unsuitable habitats. This assumption is justified by the fact that Red-billed Leiothrix populations in Liguria and Tuscany originated from a single escape of 80 individuals from an aviary in 1982 (Besagni 2000). In Latium, populations originated from multiple releases between 1998 and 2003, followed by the rapid establishment and spread of the species (Ramellini 2017).

Environmental variables

Overall, we considered ten environmental variables, describing landscape (percentage cover of agricultural areas, broadleaved forests, shrubs and bushes, and urban areas; distance from rivers), climatic conditions (total annual precipitation, precipitation seasonality, mean annual temperature, and temperature seasonality), and altitude (Table 2). Moreover, we calculated road density within the 1 km^2 cell, on the basis of road maps obtained from the Geofabrik OpenStreetMap server (www.geofabrik.de), as it is a major factor determining accessibility and the availability of biodiversity data, particularly in citizen science data (Ficetola *et al.* 2013, Merow *et al.* 2016). All variables were at the 1 km^2 resolution.

Landscape variables

To obtain land-cover information we used the CORINE Land Cover Map of Europe (European Commission *et al.* 1994), which has been successfully used to model invasion risk (Ficetola *et al.* 2010, Polce *et al.* 2011, Gallien *et al.* 2012). From this map, we extracted four layers, representing the percentage cover of four different land-cover classes at the 1 km^2 resolution: broadleaved forests, shrubs and bushes, agricultural, and urban. The Red-billed Leiothrix tends to occupy broadleaved forested areas both in the native and in the invaded range (Herrando *et al.* 2010, Collar *et al.* 2017, Ramellini 2017). Therefore, we expected that the broadleaved variable would contribute significantly to model performance. Coniferous forests are important in the native range (Collar *et al.* 2017), but in the native range coniferous woods have a different species composition compared to the invaded range (Blasi *et al.* 2014, Collar *et al.* 2017). Furthermore, coniferous forests have a negligible cover in the study area. Therefore, this variable was not included in our models. We also considered agricultural and urban cover because human-dominated landscapes have multiple impacts on invasive species (Case 1996, Pârâu *et al.* 2016). Broad-scale analyses found that the Red-billed Leiothrix is more frequent in areas with high human population densities (Pereira *et al.* 2020), however many authors found these areas to represent unsuitable habitats for the species (Amano & Eguchi 2002b, Herrando *et al.* 2010, Ramellini 2017). Furthermore, Pereira *et al.* (2020) suggested that the occurrence of the Red-billed Leiothrix in highly populated 50 × 50 km cells indicates a spread of the species in the natural habitats near urban areas. Therefore, in our fine-scale analyses we expected areas with a high urban cover to represent unsuitable habitats for the Red-billed Leiothrix.

We extracted the distance from rivers from a vectorial map of Italian rivers, downloaded from the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) geoportal (www.sinanet.isprambiente.it). This variable was measured as the distance of the centroid of each cell from the nearest cell containing a river. Other studies found that the presence of rivers is a factor influencing the distribution of the Red-billed Leiothrix, which tends to select nest sites near streams, guided by the greater food availability in freshwater ecosystems (Fisher & Baldwin 1947, Amano & Eguchi 2002a). Nesting near rivers could also influence behavioural trade-offs and possibly increase the fitness of the species (Zhang *et al.* 2016). Moreover, the species could use rivers as pathways for expansion and colonization of new areas (Ramellini 2017). We did not consider variables representing the cover of lakes and wetlands as there is no evidence of Red-billed Leiothrix preference for these environments.

Climatic variables

Climatic variables are fundamental determinants of the distribution and spread of alien species (Guisan *et al.* 2017). We retrieved climatic variables at the 1 km^2 scale (average of the period 1979–2013) from the CHELSA (Climatologies at high resolution for the Earth's land surface areas) climate dataset (Karger *et al.* 2017). We considered four climatic variables representing availability and seasonality of water and energy: total annual precipitation, precipitation seasonality, mean annual temperature, and temperature seasonality. Precipitation seasonality and temperature seasonality represent respectively the standard deviation (sd) and the coefficient of variation (CV) of mean monthly values. Precipitation variables are known to be particularly relevant for the species in Japan (Amano & Eguchi 2002a). Before running the analyses, we measured pairwise correlation between variables (online Table S1) and we did not consider altitude in the analyses because of its strong correlation with the annual mean temperature ($r = 0.91$). The correlations between the other variables were always <0.7 (Table S1), suggesting the lack of major collinearity issues (Dormann *et al.* 2012).

Species distribution modelling

We used maximum entropy modelling (Maxent; Phillips *et al.* 2006) to assess relationships between Red-billed Leiothrix distribution and environmental variables. Maxent is among the most widely used methods in species distribution modelling (Gomes *et al.* 2018). It makes use of presence/background data and is, therefore, highly suitable to model citizen science data, with an excellent performance among the SDM approaches (Elith *et al.* 2006, Elith *et al.* 2011, Peterson *et al.* 2011). Engler *et al.* (2017), in a review about SDM in birds, showed that models of this kind help to gain a better insight into the processes underlying the spread of invasive alien species. Furthermore, Maxent is among the models with the highest transferability, i.e. it has excellent performance in predicting suitability outside the calibration areas (Qiao *et al.* 2019).

Model settings

When assessing relationships between species occurrence and environmental variables, we only considered linear and quadratic terms to avoid overfitting (Phillips *et al.* 2006, Herrando *et al.* 2010). Areas that are easily accessible or better surveyed are spatially biased (Phillips *et al.* 2006, Ficetola *et al.* 2013), so that some areas can be overrepresented or underrepresented (Phillips *et al.* 2009, Kramer-Schadt *et al.* 2013). In our analyses, we assumed that areas with a higher density of roads were more frequently sampled and thus overrepresented in our models. We, therefore, included the variable 'roads density' as a bias file in all our models, both for the background and the sampled areas (Kramer-Schadt *et al.* 2013). Species distribution models require the selection of background data or pseudo-absences within a buffer zone defined around all the presence-points, representing areas that are actually accessible to the study species (Phillips *et al.* 2009, Godsoe 2010), thus our background points

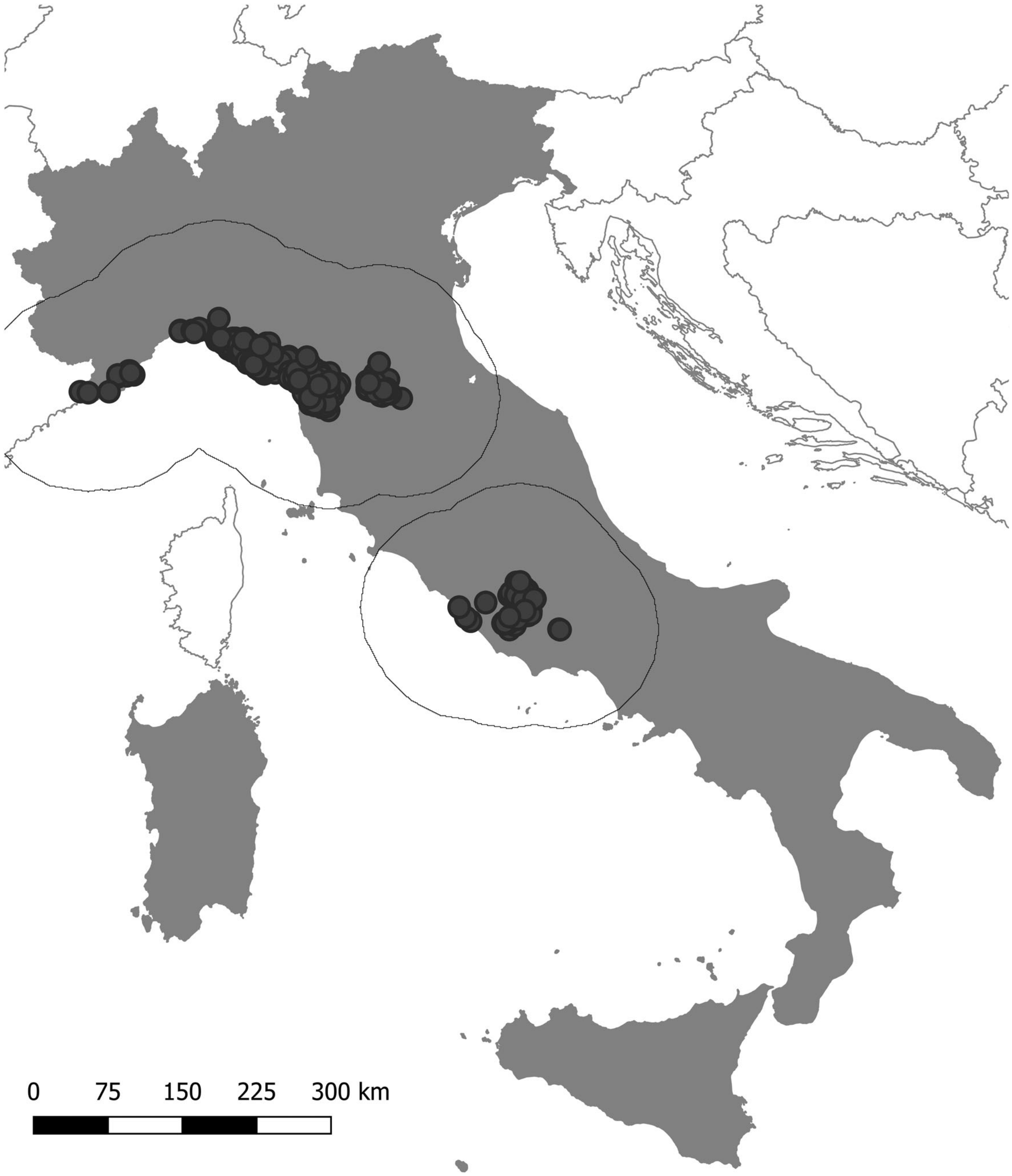

Figure 1. Distribution of the occurrence points used for building species distribution models in Italy. Black lines indicate the region from which the background points were selected.

were obtained within a buffer of 100 km from the presence records (Gallien *et al.* 2012). Within the buffer (Figure 1), we excluded points outside Italy and in marine areas.

Modelling workflow and accuracy tests

We followed a modelling workflow aimed at maximizing the robustness of predictions while minimizing the impacts of sampling bias (Nogués-Bravo 2009, Bahn & McGill 2013). We considered occurrences of the Red-billed Leiothrix from Tuscany and Liguria as belonging to a single group of populations as, even if individuals originated from different escape events, populations are currently merged (Figure 1). Therefore, we aggregated data from Liguria and Tuscany, and we considered data from Latium as part of an independent population. We ran separate models for each of the two study populations, using the second population as a test dataset to assess model performance. First, we built SDMs using the Liguria–Tuscany data for training and used the Latium for model validation. Second, we built SDMs using the Latium data for training and used the

Liguria–Tuscany data for model validation. The validation in a different study area is among the most robust tests of model performance (Nogués-Bravo 2009, Bahn & McGill 2013, Galante Peter *et al.* 2017). To test the overall accuracy of predictions we used the area under the receiver operating characteristic curve (AUC), a frequently employed threshold-independent measure in ecological modelling (Guisan & Zimmermann 2000; for an example of its use with this species see Herrando *et al.* 2010). AUC values range from 0.5 (random output) to 1 (optimal performance). It should be noted though that the maximum achievable AUC of Maxent models is below 1 (Phillips *et al.* 2006). AUC was run on both the training dataset and the test dataset, to assess the model consistency across areas. For each region we ran three models: one with landscape variables only, one considering climatic variables only, and one considering all the variables. We then used the AUC on the validation dataset to assess the predictive performance of each model.

Full model

In order to obtain a model representing the overall habitat selected by the species in Italy, we ran a model (hereafter full model), considering all the presence records and both climatic and landscape variables. Given the lack of a validation dataset for the full model, the robustness of the model was assessed using a five-fold cross-validation (Nogués-Bravo 2009). The average model among the cross-validated ones was then projected to the whole Italy, to identify the areas most at risk of invasion outside the study regions. In SDM, extrapolations beyond the range of environmental variables observed in the training area may determine unreliable results. Therefore, we computed multidimensional environmental similarity surfaces and identified areas where SDM extrapolated onto environmental conditions that are outside the ones observed within the training range (Elith *et al.* 2010, Masin *et al.* 2014).

Results

When using Latium as training data and Liguria–Tuscany as test data, the model including both climate and landscape variables showed the highest performance (Table 1), outperforming models including climate only and landscape only. The model including both climate and landscape was the best one also when calibrated on the Liguria–Tuscany data. Both the model calibrated on the Latium data, and the model calibrated on the Liguria–Tuscany data, showed

Table 1. Performance of models calibrated on the two training regions, using all the data. For the model calibrated with all the data, the test AUC is the average of test AUC in 5 cross-validated models.

Training region	Test region	Variables	Training AUC	Test AUC
Liguria + Tuscany	Latium	Climate	0.884	0.644
Liguria + Tuscany	Latium	Landscape	0.742	0.534
Liguria + Tuscany	Latium	Climate + landscape	0.900	0.646
Latium	Liguria + Tuscany	Climate	0.929	0.690
Latium	Liguria + Tuscany	Landscape	0.736	0.602
Latium	Liguria + Tuscany	Climate + landscape	0.941	0.704
Liguria + Latium + Tuscany	-	Climate + landscape	-	0.873

a good ability to predict the test dataset of the other region, suggesting robustness of the model (Table 1).

Red-billed Leiothrix potential distribution

By projecting the full model to the whole Italy, we identified two main areas with high suitability for the Red-billed Leiothrix: (i) a band of medium/high suitability stretching from the western corner of Liguria (NW Italy) to the Tyrrhenian side of Calabria (southern tip of continental Italy) and (ii) in lowland and hilly areas of northern Italy, immediately South of the Alps (Figure 2). In Sardinia and in portions of Sicily, Calabria, Apulia, and northern Italy, environmental conditions were mostly outside the range found in the calibration range, thus predictions were not considered for these regions (Figure 2).

Variables explaining habitat suitability

When we built the full model, precipitation seasonality, percentage of agricultural cover, annual mean temperature, and temperature seasonality were the most important variables in terms of percentage contribution to explain Red-billed Leiothrix distribution. Distance from the nearest river, broadleaved cover, and percentage cover of urban areas had limited importance (Table 2). Red-billed Leiothrix habitat suitability was highest in areas with low agricultural cover, high annual precipitation, and intermediate precipitation seasonality (Figure 3). Furthermore, suitability was highest in areas with high annual mean temperature (Figure 3(b)).

Discussion

Our results showed that a further expansion of the Red-billed Leiothrix in Italy is likely on the northern and western sides of the peninsula, in agreement with our

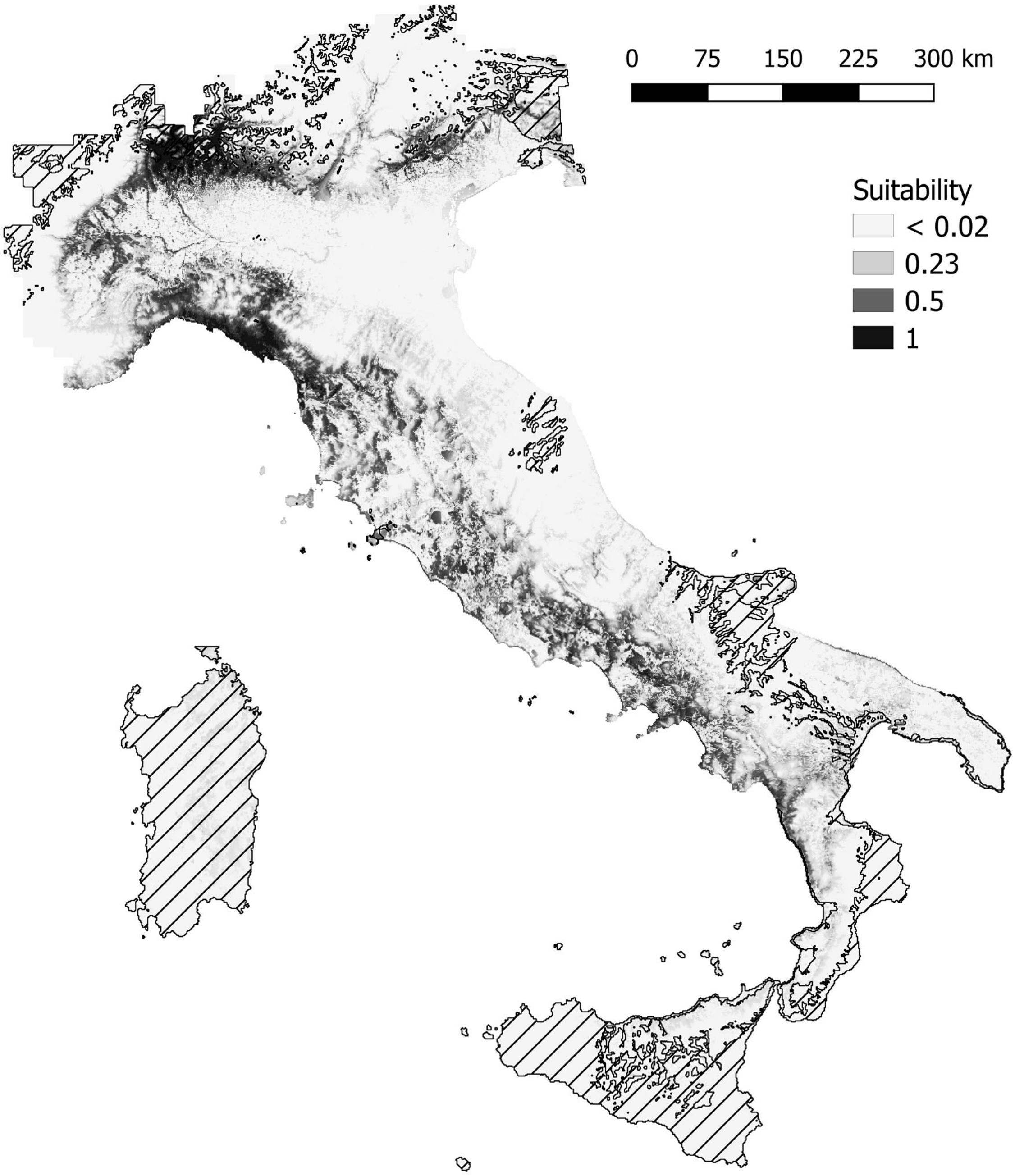

Figure 2. Habitat suitability map for the Red-billed Leiothrix in Italy. Suitability thresholds are set at the minimum training presence threshold (0.02) and at the 10-percentile training of the presence threshold. Barred areas represent regions where the model is extrapolated outside the conditions present in the calibration area.

hypothesis that this species has the potential to attain a wider distribution in Italy. We provided indications on the factors that could shape Red-billed Leiothrix expansion and confirmed the joint importance of climate and landscape variables to understand the distribution of this species (Bradie & Leung 2017). Some regions where the species is known to occur outside Liguria, Latium, and Tuscany, for instance, the northeastern area of Piedmont (Grimaldi 1992), were correctly predicted as suitable from the full model.

Climatic variables

Climatic variables were very important in explaining the distribution of the Red-billed Leiothrix, in agreement with the hypothesis that these factors are key drivers of the spread of invasive birds (Pereira *et al.* 2020, Table 2). Our work suggests that rain regimes in the invaded region can significantly affect the distribution of this species (Table 2). The response curve for annual precipitation showed the highest suitability in areas with precipitation over 1000 mm

Table 2. Environmental variables considered in the species distribution models, and percentage contribution of the variables in the average model.

Name	Variable	% Contribution
Bio15	Precipitation seasonality	32.52
Agricultural	Percentage cover of agricultural areas	28.29
Bio1	Annual mean temperature	14.13
Bio4	Temperature seasonality	10.39
Bio12	Annual precipitation	8.43
Heterogeneous	Percentage cover of shrubs and bushes	3.09
Urban	Percentage cover of urban areas	1.98
Broadleaved	Percentage cover of broadleaved forests	1.17
Distance from rivers	Distance from the nearest river	0.0003

per year, i.e. values higher than those typical for a Mediterranean climate (Allaby 2015). Such a match with high precipitation values is in agreement with observations from the invasion of the Red-billed Leiothrix in Japan and other areas of Europe (Amano & Eguchi 2002a, Pereira *et al.* 2020) and is not unexpected given that the species is also a native of rainy regions of China (Zhang *et al.* 2016). When discussing the factors influencing the Red-billed Leiothrix invasion in the Hawaiian Islands, Fisher & Baldwin (1947) considered rainfall to be 'apparently' not a determining factor. However, it should be remarked that in Hawaii average precipitation is much higher than in Mediterranean regions, and thus it is probably not a limiting factor. As precipitation seasonality influences plant diversity in Mediterranean ecosystems (Clary 2008), the preference of the species for intermediate values of precipitation seasonality might be related to the association with particular plant communities. The response curve for annual mean temperature indicated higher suitability at increasing values of temperature, highlighting a preference of the Red-billed Leiothrix for warmer climates. In our suitability map, the majority of the cells with the highest suitability fell within areas characterized by a Mediterranean climate. The establishment of self-sustaining populations of Red-billed Leiothrix across other areas with a Mediterranean climate is well known (Dubois 2007, Herrando *et al.* 2010, Pereira *et al.* 2020), suggesting that in its European range the species can occupy niches different from the native ones. This process can be due to niche unfilling of the species (Petitpierre *et al.* 2012, Strubbe *et al.* 2013), and additional studies are required to evaluate this hypothesis.

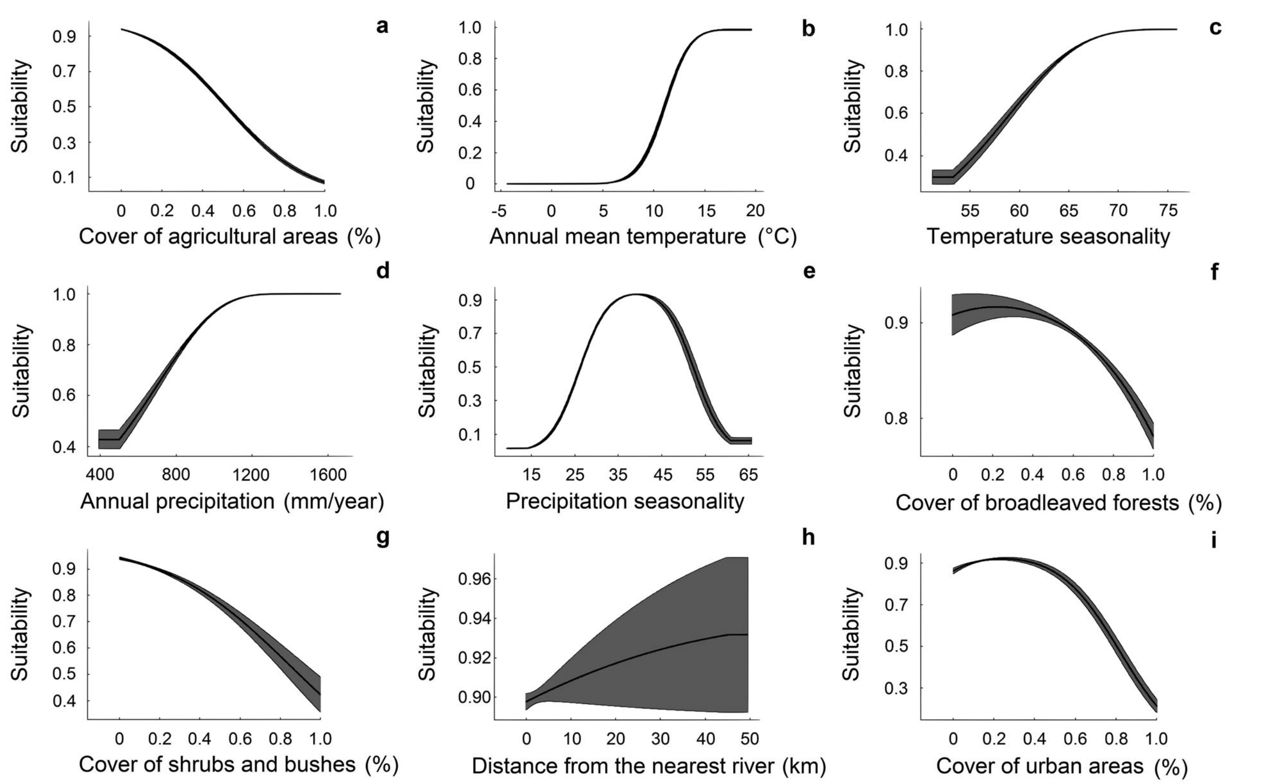

Figure 3. Response curves showing the relationship between environmental variables and suitability (in logistic output) for the Red-billed Leiothrix: (b–e) climatic variables; (a, f, g, i) land-use variables; (h) distance from rivers. For each graph, the grey shades represent one standard deviation computed on the basis of a five-fold cross-validation.

Landscape variables

Among the landscape variables, agriculture showed the highest importance in explaining the Red-billed Leiothrix distribution. Suitability decreased in the areas with highest agricultural cover, in accordance with previous studies in Italy and in other invaded areas, where the species tends to occupy rather natural, undisturbed habitats (Amano & Eguchi 2002b, Herrando *et al.* 2010, Ramellini 2017). This is in contrast with the general pattern shown by bird invasive alien species which are often associated with open and disturbed habitats (Case 1996, Duncan *et al.* 2003, see also Pereira *et al.* 2020). In our study, distance from the nearest river showed minor importance compared to the other variables. This result could be explained considering that we did not focus on the nesting period, which was the focus of some previous studies underlining the importance of water ecosystems for the species (Zhang *et al.* 2016). Furthermore, our analysis was performed at a rather coarse scale (1 km^2): it is possible that we did not capture processes occurring at the microhabitat level (e.g. small streams). The cover by broadleaved forests showed limited importance. This result is not in agreement with our second hypothesis, nor with studies suggesting that forests are a key driver of Red-billed Leiothrix distribution (Herrando *et al.* 2010). This could occur because of the differences between the two areas used to calibrate the models, and because of differences in forest composition that are not captured by broad-scale habitat maps, which are not able to distinguish among typologies of broadleaved forests with different composition or tree density. Advances of remote sensing techniques promise great improvements in our ability to measure habitat at high resolution and could allow us to better describe fine-scale habitat variation, thus allowing enhanced understanding of species distribution (Ficetola *et al.* 2014).

Outlook

Our results provide fine-grained, baseline information for the prevention of Red-billed Leiothrix colonization in uninvaded areas. They can also contribute to drawing up management plans for the species both at the local and national levels. Our study further highlights the importance of developing SDMs to assess the invasive potential of alien species. Given the high invasive potential of this babbler, and the known major impacts on native species (Martin-Albarracin *et al.* 2015), we suggest its possible inclusion in the list of alien species of European concern (Regulation EU No. 1143/2014). For a proper interpretation of SDMs results and for the definition of future lines of research it is necessary to acknowledge the limitations and assumptions of each modelling technique (Ficetola *et al.* 2010, Araújo & Peterson 2012, Engler *et al.* 2017, Barbet-Massin *et al.* 2018). In our work, we assumed a constant land-use and climate through time as we did not consider historical variations in the environmental conditions. Dynamically modelling the distribution of the species could help in refining our predictions (Brambilla *et al.* 2010). As we did not take into account variations in the species distribution, possible future lines of research could be aimed at defining past patterns of invasion to better understand invasion dynamics and extrapolate further predictions (Ficetola *et al.* 2010). The information we provide could be profitably combined with studies employing connectivity, in order to evaluate the potential spread of the Red-billed Leiothrix while integrating information on landscape connectivity and to identify potential corridors of invasion (Cowley *et al.* 2015, Falaschi *et al.* 2018). Future work should also be done to refine our knowledge on the environmental conditions that favour the species in the Mediterranean region at a finer spatial scale, e.g. an *in situ* evaluation of population growth rates could help to define the population-persistence niche for this babbler.

Acknowledgments

We thank all the observers who provided data and we especially thank N. Bonassin, M. Coppola, E. Mori, R. Nardelli, and G. Tellini Florenzano for providing clustered data, P. Ramellini, E. Mori for comments on the text, D. Rubolini, A. Galimberti, and M. Bertoncini for technical advice. We are also grateful to the anonymous reviewer and the editor for their helpful comments on the manuscript.

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