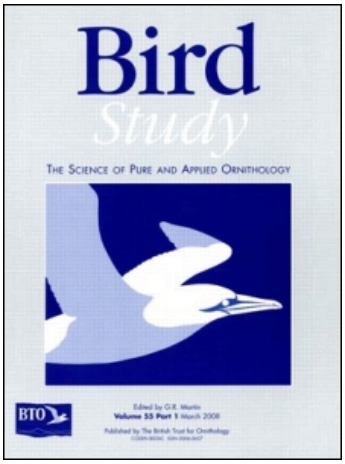

Bird Study
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t904369352

A new exotic bird in Europe: recent spread and potential range of Red-billed Leiothrix *Leiothrix lutea* in Catalonia (northeast Iberian Peninsula)

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Online publication date: 21 May 2010

To cite this Article Herrando, Sergi , Llimona, Francesc , Brotons, Lluís and Quesada, Javier(2010) 'A new exotic bird in Europe: recent spread and potential range of Red-billed Leiothrix *Leiothrix lutea* in Catalonia (northeast Iberian Peninsula)', Bird Study, 57: 2, 226 — 235
To link to this Article: DOI: 10.1080/00063651003610551
URL: http://dx.doi.org/10.1080/00063651003610551

Bird Study (2010) **57,** 226–235

A new exotic bird in Europe: recent spread and potential range of Red-billed Leiothrix *Leiothrix lutea* in Catalonia (northeast Iberian Peninsula)

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Capsule Following recent introduction in Spain, Red-billed Leiothrix have the potential to attain a wide distribution in Catalonia and probably in other parts of Europe.
Aim To investigate past, present and potential distribution of this exotic species in Catalonia (northeast Iberian Peninsula).
Methods We collected data on the species' occurrence over the period 1992–2008 and used information obtained in other regions where it has previously established to produce hypotheses about the ecological processes that affect its population increase and range expansion. We then generated fine-grained distribution maps covering the entire region for the periods 1992–2001 and 2002–2008, and for the species' potential range according to its specific habitat requirements.
Results Since being first detected in the wild in the Collserola Park, near the city of Barcelona, Red-billed Leiothrix have expanded to neighbouring forested areas. The wild population is currently in a phase of exponential growth and, according to our habitat suitability model, the species' potential distribution in Catalonia might be 36 times greater than at present.
Conclusion Our results suggest that the Red-billed Leiothrix has the potential to attain a widespread distribution over large regions of Europe in the near future. However, we discuss several factors that might affect these predictions.

The establishment and spread of introduced species is recognized as one of the major threats for biodiversity worldwide (Elton 1958, Mack *et al.* 2000), and the risks associated with this phenomenon are likely to increase in the near future owing to current rates of international transportation and global biological exchange (Ricciardi *et al.* 2000). Researchers have attempted to model the spatial patterns of range expansion after initial invasions, and hypotheses regarding the ecological processes involved in the geographical extent of invasive species usually take into account the ecological niche of the species in their native areas (Peterson & Vieglais 2001). However, this approach may be of limited value when the species has become established in regions that are environmentally very different from those of the species' original distribution. Thus, it may be easier to predict the spread of an exotic species in a recently colonized area if we take into account the ecological conditions of the non-native regions in which the species is found.

Birds are excellent biological models for the study of species invasions since many introductions have been studied extensively, and these well-known historical events may provide valuable opportunities to test hypotheses that cannot be conducted experimentally because of their cost or ethical considerations (Duncan *et al.* 2003). In this context, Red-billed Leiothrix *Leiothrix lutea* represent a good model for studying the spread of an exotic species in new regions. The natural range of this babbler (Timallidae) is restricted to the Himalayas, southeast China and adjacent areas, though man-induced range expansions have occurred in Hawaii, Réunion Island, Japan, and

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a number of scattered localities in Europe (Collar & Robson 2007). In Spain, Red-billed Leiothrix occupy mountains close to the city of Barcelona (Martí & del Moral 2003, Llimona & Sales 2004, Llimona *et al.* 2007), and in France the species has become established in scattered areas such as Île-de-France, Béarn (western Pyrenees) and the Provence-Alpes-Côte-d'Azur region (Dubois 2007). Furthermore, the case of Red-billed Leiothrix is particularly interesting from an ecological point of view since it inhabits evergreen broadleaved and pine forest habitats with dense understory in its original distribution, and other forest types in areas where it has become successfully established, contrasting with the patterns shown by most introduced birds, which are primarily occupants of open and disturbed habitats (Case 1996). In Japan, the species occurs in a great variety of deciduous or mixed forests if the cover of bamboo understory is tall enough (Amano & Eguchi 2002, Tojo & Nakamura. 2004). In Hawaii, the species is present in both native and exotic tropical forests with a well-developed understory (Scott *et al.* 1986).

The extent of habitat or environmental conditions suitable for an introduced species should ultimately constrain its potential distribution in new locations (Duncan *et al.* 2003). Considering the diverse habitat selection shown by Red-billed Leiothrix in other regions, habitat availability seems far from being a limiting factor over large areas of Europe. This could be particularly important in the European Mediterranean Basin, where woodlands have sharply increased during recent decades as a result of land abandonment (Blondel & Aronson 1999, Debussche *et al.* 1999), and this has favoured a general increase in the ranges of forest bird species (Preiss *et al.* 1997, Gil-Tena *et al.* 2009).

This study describes the recent expansion of Red-billed Leoithrix in Catalonia (northeast of the Iberian Peninsula) between 1992 and 2008, uses habitat data recorded in other areas where the species has become established successfully, and produces spatially-explicit hypotheses regarding its past, present and potential future distribution in this region.

METHODS

Study area

Catalonia is a region of c. 32 000 km characterized by high habitat diversity, from coastal marshes to alpine meadows and steppes. There is currently a high degree of forest cover in the region (38%), providing an interesting framework to study the expansion of an introduced forest species such as Red-billed Leiothrix. Additionally, Catalonia is a region with a highly developed infrastructure for field ornithology, as demonstrated by the recent Catalan Breeding Bird Atlas (Donald 2005).

Field records

We searched for records of this species in both standardized censuses, such as those carried out regularly to determine population dynamics, and records of casual observations. A total of 335 observations of Red-billed Leothrix were obtained. Of these observations, 58% were provided by the Constant Ringing Effort Site Scheme; 20% by the Bird Survey Scheme carried out in the Collserola Park, the protected area close to the city of Barcelona where the species was first discovered in 1992; 10% by the Catalan Common Bird Survey; 9% by the Annual Birding Reports; and 4% by the Catalan Winter Bird Atlas 2006–2009.

Periods of expansion

Landscape structure and functional connectivity are expected to play a key role in the process of colonization of new areas by an invasive species (Kimberly 2002). The Collserola Park, where the species was first detected in the wild in Catalonia, is a highly forested area, largely isolated by the Llobregat and Besòs rivers, several cities, infrastructures, and to a lesser extent by open habitats (Fig. 1). Given the likely importance of forest composition and configuration at a landscape level in the expansion of this species from its initial record in Collserola, we subdivided data into two periods: (1) 1992–2001: the period in which the observations of the species occurred only within the boundaries of the Collserola Park; and (2) 2002–2008: the period from the first observation of the species outside the continuous forested area of the Collserola Park.

Seasonality of expansion

Red-billed Leiothrix is a resident species; however, seasonal movements have been reported both in native regions (Collar & Robson 2007) and in Europe (Basly 2007). We analysed possible changes in distribution between breeding and non-breeding seasons in order to detect whether the range expansion occurred throughout the year or was concentrated in a particular season.

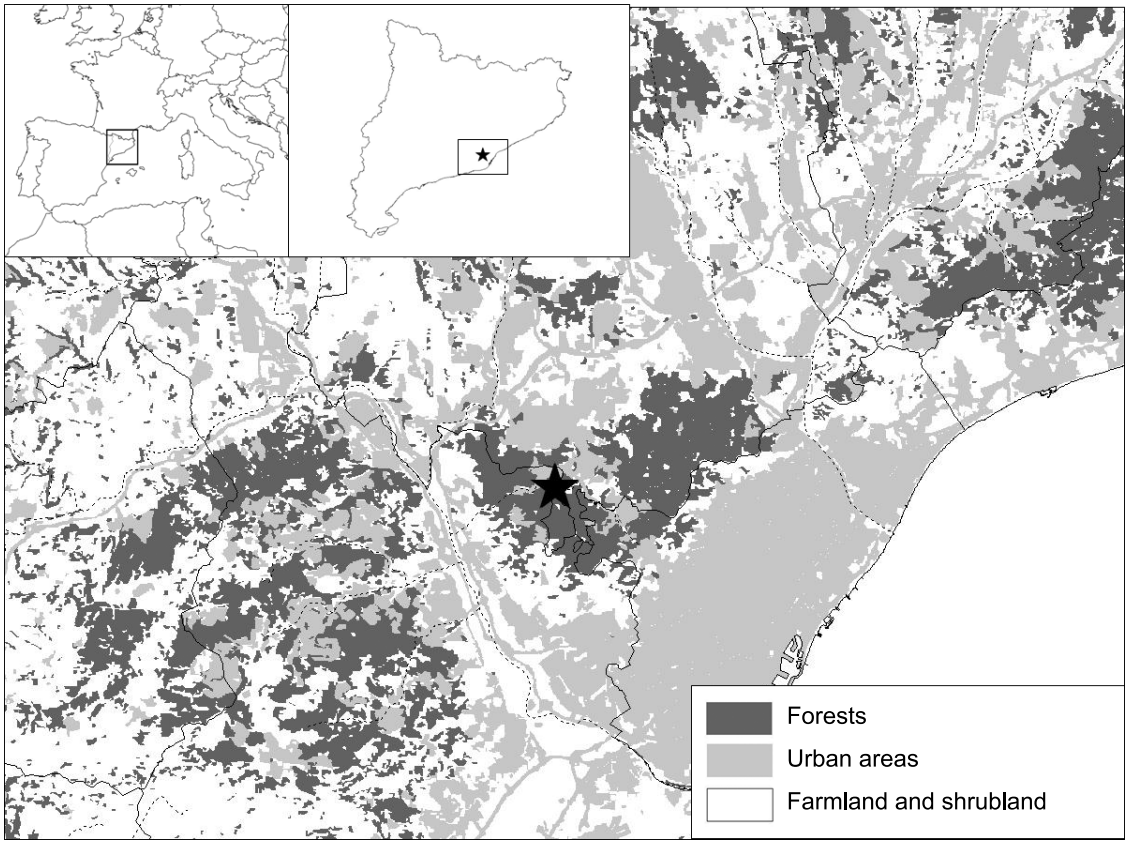

Figure 1. Location of the first record of Red-billed Leiothrix in Catalonia, which occurred in 1992. This observation (shown by a star in the map) was made in Collserola Park, a forested massif close to Barcelona. In addition to this city, other urbanized areas located in the Besòs and the Llobregat river valleys (northeast and southwest, respectively) surround this forested massif.

We defined breeding season as the period in which the incubation patch was present in captured females (Catalan Ringing Data Bank and Constant Ringing Effort Site Scheme), that is from April to August (n = 62 females with incubation patch). Thus, field records obtained within this period were considered breeding observations, whereas those of the rest of the year were considered non-breeding observations. We then used a GLM (MANOVA) to test for any distribution shift between breeding and non-breeding seasons. Hence, we used as dependent variables the x and y coordinates and season (breeding, non-breeding) and period (first: 1992–2001, second: 2002–2008) as fixed factors. Specifically, we tested if the average x and y coordinates changed between breeding and non-breeding observations in the two study periods (1992–2001 and 2002–2008).

Models of species distribution

This study attempts to investigate the changes in the distribution of Red-billed Leiothrix in two study periods (see earlier) as well as its potential distribution in Catalonia, given the current patterns of habitat selection in other already occupied regions. We modelled habitat selection of the species based on the particular set of environmental variables identified in the literature that may best predict the species' distribution. We used the Maximum Entropy approach and the software MAXENT, which is particularly appropriate for casual, presence-only data (Phillips *et al.* 2006), such as that collected in this study.

The selection of an appropriate set of predictors is usually a key issue in any modelling exercise, but becomes extraordinarily important when the observations are expected to be geographically or ecologically biased. In order to model the species distribution in the two periods of interest, we used three critical environmental variables: (1) forest cover; (2) linear distance to the first observation of the species in Collserola; and (3) a resistance variable classifying all land use according to the resistance to the movements of a forest bird species. Forest cover was selected because the literature

reports that the species inhabits deciduous, pine or tropical forests with a rich understory (Collar & Robson 2007). We therefore selected all forest types in our study region as suitable habitats for Red-billed Leiothrix, with the exception of subalpine fir and mountain pine forests, which usually have a short and sparse understorey. Furthermore, the species has never been recorded in this type of forest (Collar & Robson 2007). The linear distance to the first species record is expected to have a great importance in the prediction of species distribution if the colonization process began at a specific point and is constrained by dispersal. In the case of our study, we cannot discount the possibility of several initial introduction events, but the progressive spread of the observations around the first sighting in the centre of the Collserola range suggests that, although other population origins are possible, the distance to this point may be crucial to understanding the expansion of the species in the region. Finally, each bird species selects a particular set of habitats for dispersal and some habitats are more difficult to cross than others. We therefore categorized land uses according to their potential resistance to movements by this particular forest bird. We assumed that dispersal constraints perceived by the species were similar to that of European forest species and, therefore, used a connectivity map developed for strict forest passerines in the area (unpubl. data). Linear distance and the resistance variable were incorporated in the modelling of the species distribution in the 1992–2001 and 2002–2008 periods, but they are expected to be of little importance in a theoretical scenario in which the species has already occupied all available suitable habitat. Therefore, the only predictor included in the modelling of the potential distribution was forest cover. Other possible biotic interactions that may affect the species' potential distribution, such as competition with native species, were not included. Consequently, our model refers exclusively to a habitat potentiality model or habitat suitability model.

To generate biologically meaningful models we incorporated exclusively linear and quadratic terms of the predicted variables in the models. We used a cross-validation procedure to evaluate the accuracy of predictions (Guisan & Zimmermann 2000). This procedure consisted of dividing the data into two different sets by randomly assigning 70% of occurrence values for each species to a training data set, and the remaining 30% of occurrences to a test data set. The training data set was used to develop the MAXENT model. The area under the receiver operating characteristic curve (AUC) is a convenient measure of overall accuracy, and commonly varies between 0.5 (for chance performance) and 1.0 (perfect discrimination). According to this data set subdivision, we assessed the AUC values for each of the three distribution models (1992–2001, 2002–2008 and potential) to evaluate their accuracy. In addition, we evaluated the model conducted for the 1992–2001 period with data from the 2002–2008 period as a way of estimating the accuracy of our analytical approach as a predictor of the species' distribution in the near future.

RESULTS

The number of observations of Red-billed Leiothrix over time fitted an exponential distribution for the period 1992–2008 ($r = 0.82$, $P < 0.001$, $n = 16$; Fig. 2). This increase could be partially related to an increase of observers in Catalonia over time since, at least in the period for which we have reliable data (1996–2008; from the Annual Birding Reports), these two variables were highly correlated ($r = 0.94$, $P < 0.01$, $n = 9$; three years with no data). However, we found no relationship between the number of observers and the number of observations of Red-billed Leiothrix ($r = 0.59$, $P = 0.11$, $n = 9$).

Seasonality of the expansion

The process of colonization of new areas differed between the study periods and seasons (Fig. 3) as shown by the results generated by GLM analysis. Regarding the longitudinal shift, no significant differences between breeding and non-breeding season were detected for the 1992–2001 period (*post-hoc* honestly significant difference [HSD], $P = 0.998$), whereas we found a significant difference between breeding and non-breeding season for the 2002–2008 period (*post-hoc* HSD, $P < 0.001$). In the case of the latitudinal shift there was no significant difference between breeding and non-breeding seasons in the 1992–2001 period (*post-hoc* HSD, $P = 0.681$), whereas we found significant differences between breeding and non-breeding season in the 2002–2008 period (*post-hoc* HSD, $P < 0.001$). As a whole, we detected a geographical shift towards the northeast, which was more evident in the non-breeding season (Fig. 4).

Past, present and potential range

A total of 85 observations of Red-billed Leiothrix were collected for the 1992–2001 period, all of them within

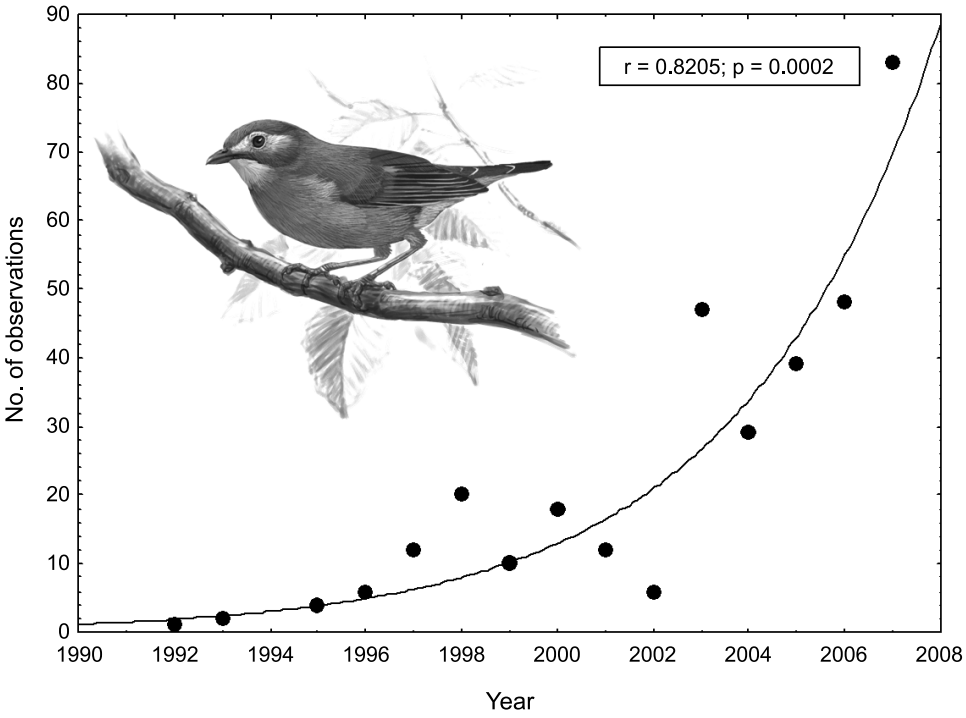

Figure 2. Number of observations of Red-billed Leiothrix in Catalonia since the first sighting in 1992 to early 2008. These observations refer to the number of individuals recorded each year, either by sight, vocalizations, or captured and ringed.

the boundaries of the Collserola Park (Fig. 5). In December 2002, the species was detected for the first time outside Collserola Park, in Serra de Marina Park, 17 km northeast of the species' first observation and 8 km from the closest previous observation. The training data for the model of the 1992–2001 period had an AUC = 0.999, the same value obtained for test data. This model was also a good predictor of the data from the 2002–2008 period (AUC = 0.993). In the 2002–2008 period, 270 Red-billed Leiothrix observations were obtained, with 79 observations outside Collserola Park (29%), all of them except two around the point were the species was detected for the first time in Serra de Marina Park (Fig. 5). The model conducted using these data was also highly accurate (AUC training data = 0.995, AUC test data = 0.994).

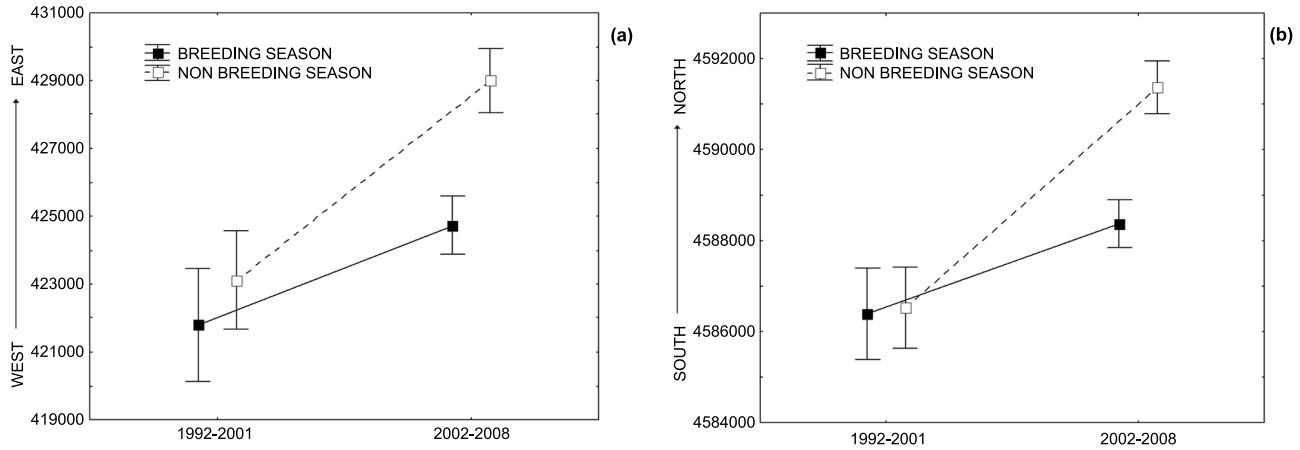

Figure 3. Longitudinal (a) and latitudinal (b) shift between breeding and non-breeding seasons in the location of field observations of Red-billed Leiothrix. The Y-axis indicates the universal transverse Mercator coordinates (in metres).

Bars indicate 95% CI.

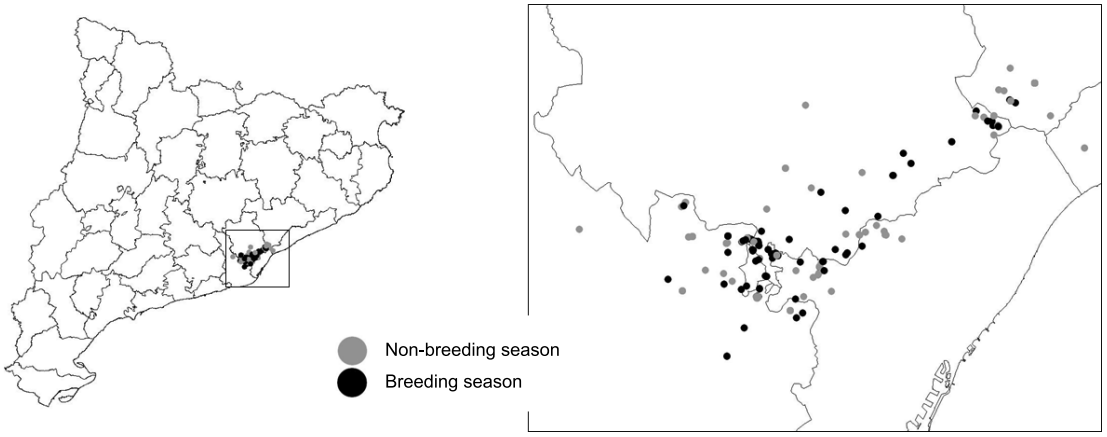

Figure 4. Locations of the observations of Red-billed Leiothrix in Catalonia (left) with a zoom into the area where the species has been recorded to date (right). Non-breeding and breeding reports are shown separately.

Modelling the potential distribution of Red-billed Leiothrix in Catalonia was based exclusively on forest cover variables and showed a relatively low accuracy (AUC training data = 0.702, AUC test data = 0.634). Considering that the species is present at a conservative threshold of probability of occurrence ≥0.6, its current distribution would be estimated at 148 km^2, whereas the potential distribution according to the habitat model would be 5993 km^2 (Fig. 6).

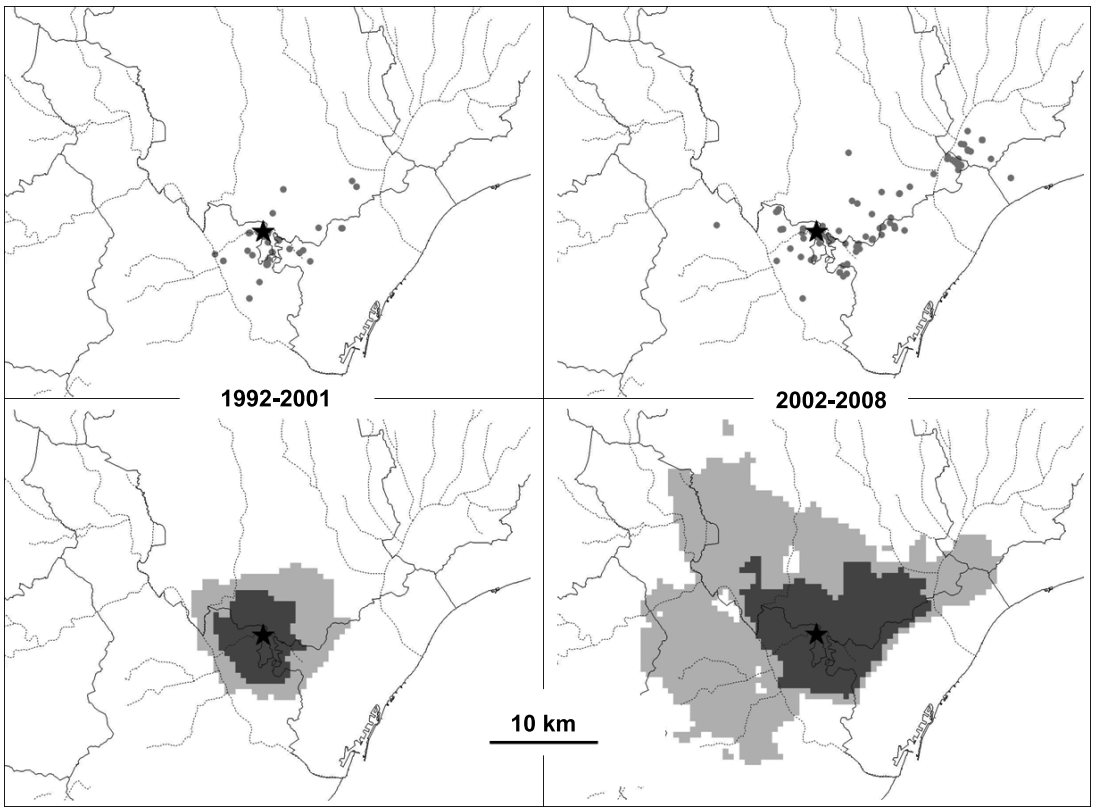

Figure 5. Locations of field records (above) and MAXENT models (below) for the two study periods. The MAXENT models show the occurrence of the species with 0.3–0.6 (light grey) and 0.6–1.0 (dark grey) probability of occurrence. The star shows the point where the species was first detected in 1992.

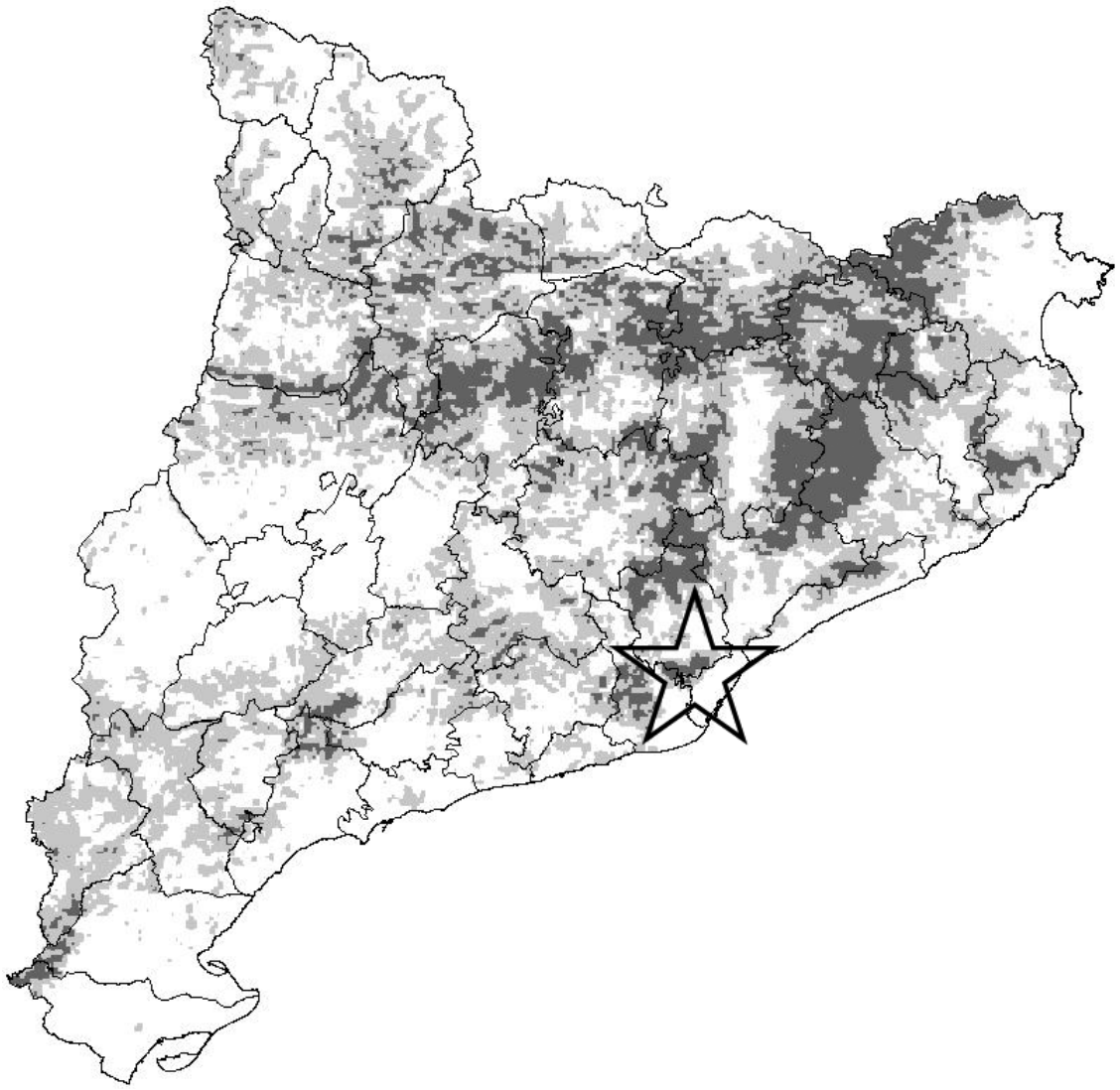

Figure 6. MAXENT model showing the potential distribution of Red-billed Leiothrix in Catalonia based on its reported habitat requirements, with 0.3–0.6 (light grey) and 0.6–1.0 (dark grey) probability of occurrence. The star indicates the area where the species was first located in Catalonia, in 1992.

DISCUSSION

We have described the recent expansion of Red-billed Leiothrix in Catalonia, one of the few regions where this exotic bird species has established in Europe and one of the first worldwide with a Mediterranean climate type (see also Dubois [2007] for localities near the Mediterranean in France). Although this species has its origin in a subtropical region, available data suggest that it is becoming a successful invader in the Mediterranean Basin. As shown by the studies of Kark & Sol (2004), this biogeographical cross-over is not an exception among bird introductions in Mediterranean ecosystems, where those species that come from other regions characterized by a Mediterranean climate have not demonstrated greater success in becoming established than species from other biogeographical origins.

Red-billed Leiothrix inhabit forest understory, a habitat where visual contact with birds is often low (Bibby & Buckland 1987). In addition, this is a new species in Catalonia and its song and calls could be mistaken by a non-trained ornithologist for those of other forest passerines such as Blackcaps *Sylvia atricapilla* and Common Blackbirds *Turdus merula*. This could potentially produce some geographical bias related to presence/absence of trained observers in the different areas of the study

region. However, we consider that the current coverage of monitoring projects in Catalonia (see, for instance, www.sioc.cat; SOCC [Catalan Common Bird Survey] monitoring scheme) is good enough to minimize this potential geographical bias.

From the first records of Red-billed Leiothrix in Catalonia in 1992, the number of observations has followed an exponential curve. This suggests an exponential spatial spread of the species, the typical shape of the initial phases of many biological invasions (Domènech *et al.* 2003, Crooks 2005). Our data indicate that the species has crossed the two highly urbanized river valleys surrounding the Collserola Park, which implies crossing a gap of non-suitable habitat of almost 1 km in the case of the Besòs river (northeastwards), and somewhat more than 2 km in that of the Llobregat river (southwestwards). It could be argued that the individuals found in these new localities might come from new escapes and not from the nearby Collserola population. However, the closest location of Besòs was colonized by the species five years before the farther location of Llobregat, supporting the hypothesis of a natural process of expansion from Collserola and the role of habitat connectivity as a determinant predictor of its distribution.

The distribution of the species did not differ between breeding and non-breeding seasons during the first decade after colonization prior to the emergence of the exponential population increase. However, during the second decade new locations were reported, mainly during the non-breeding season. This suggests that in the first years after the colonization the species' expansion was constant throughout the year, but was concentrated during the non-breeding season in the second decade of colonization. Although no age data for individuals are available, it is possible that many of these non-breeding records situated in the borders of the range correspond to juveniles. This would be consistent with data collected in Hawaii, where young individuals have been observed far from their breeding grounds (Male *et al.* 1998). Differences between the two study periods could be related to the fact that juveniles usually settle close to their parents in the initial phase of colonization, whereas they start to move further away when species density reaches a threshold. Unfortunately, no recaptures of ringed individuals further than 1 km from the net in which they were first captured have been obtained so far in Catalonia (Catalan Ringing Office, unpublished data), which limits interpretations of individual dispersal capacity and age of the dispersers. There is a need for more studies considering capture–recapture or gene-flow analysis in order to understand the population dynamics associated with this expansion.

Currently, the European range of Red-billed Leiothrix is restricted to specific localities in France, Italy, Germany and Spain (Collar & Robson 2007). This babbler species is frequently kept as a wild-caught pet, which strongly increases the likelihood that escaped individuals will be successful invaders compared with captive-bred species (Carrete & Tella 2008). Consequently, new centres of expansion might occur in Europe in the near future. In addition to these new introduction events, the potential for the species' expansion should be carefully considered. According to the calculations derived from our habitat suitability models, and considering a conservative threshold of probability of occurrence ≥0.6, the potential range of this species in Catalonia could be 36 times larger than at present.

The spread of Red-billed Leiothrix is well documented in Hawaii, where it has been present for more than a century, with populations that have fluctuated widely on different islands and even gone extinct on some islands (Male *et al.* 1998). Although the causes of these dramatic population fluctuations remain unknown (Male *et al.* 1998), they may represent a critical point in the expansion of the species in non-native areas. These events offer valuable lessons about the real capacities of the species to reach its predicted potential range according to habitat suitability models. In general, widespread over-prediction in projecting niche models onto landscapes is attributable in large part to historical factors that limit species' geographic distributions at medium to large spatial scales (Peterson & Vieglais 2001).

There has been evidence of damaging effects on biota caused by birds. Non-indigenous birds can promote homogenization of the natural avifauna (MacGregor-Fors *et al.* 2010), as well as parasite transmission, competition, hybridization or economic damage (see a revision in Sol *et al.* [2005]). To date, there is no evidence that Red-billed Leiothrix has provoked any clear ecological disruption, either in the study area (Llimona & Sales 2004), Japan (Amano & Eguchi 2002), or in the French western Pyrenees (Basly 2007). Different time lags can be found throughout the invasion process, including the arrival, establishment, and impacts of invaders, and they can become more aggressive over time, increasing their impact on native species (Crooks 2005). Accordingly, the areas where the species has been introduced for

the longest time would be more prone to showing any adverse effects of the species on the native ecosystems. In Hawaii, where the introduction of the species dates from 1911, Red-billed Leiothrix does not appear to exert any noticeable adverse effects on populations of native birds, at least directly. However, the species has been reported as a vector for the spread of the introduced plants on whose fleshy fruits they feed (van Riper *et al.* 1986).

This study stresses the importance of spatial modelling techniques in order to determine current and potential ranges of introduced bird species. Although the population dynamics of invaders may be complex, the determination of these ranges under consistent hypotheses may contribute to understanding the spread of non-native species in introduced habitats, providing useful tools to study their interactions with native ecosystems, and in some cases, to design effective control planning measures (Corsi *et al.* 1999, Muñoz & Real 2006).

ACKNOWLEDGEMENTS

This study has been possible thanks to the observations reported by the biologists of the Estació Biològica Can Balasc: Anna Tenés & Seán Cahill, and of many other field ornithologists who have communicated their Red-billed Leiothrix observations to the Catalan Ornithological Institute. Among them, we should mention Raül Calderón, Javier Cotín, Antonio España, Ángel Fernández, Joan Carles Fernández, Carles Furquet, Ernest Garcia, Xavier Moreno and Sergi Sales. Carlos Pons performed a crucial task in the creation of suitable databases from such diverse data origins. Magda Pla provided invaluable support in the calculation of predictor variables. Comments and corrections from Katherine Renton, Marc Anton and Santi Guallar greatly contributed to the final manuscript. Finally, we thank Toni Llobet for the illustration of the Red-billed Leiothrix shown in this manuscript. The bird monitoring projects coordinated by the Catalan Ornithological Institute have the support of the Department of Environmental and Housing of the Catalan Government. This work was conducted by the Catalan Research Group 2009 SGR 1467.

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(MS received 14 August 2009; revised MS accepted 11 January 2010)