



OPEN Changes of nestling ringing dates in nine bird species over seven decades

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Climate change co-occurs with an advancement of avian breeding season (indexed as laying dates or fledging dates) in the temperate zone, suggesting a causality between them. Here, we investigate whether the long-term shifts in nestling (chick) ringing dates also mirror this phenomenon. This index is biased by inherent shortcomings, such as the non-independence of dates (in nestmates, colony members), poor accuracy (long period suitable for ringing), and strange shape of distributions. These shortcomings can be reduced by applying the median of annual ringing dates as an index of breeding phenology. The advantage of this index is that data are available for long periods and large sample sizes. By accepting certain compromise between statistical discipline and fieldwork realities, we examined changes in the breeding phenology of 9 bird species from 1951 to 2020 in Hungary. We found that the annual median of ringing dates advanced significantly (by 9–14 days) in the Black-headed Gull, Common Kestrel, Barn Swallow, Great Tit, and Eurasian Blue Tit. Contrarily, no significant (all $P > 0.16$) changes occurred in the case of the Common Tern, Black-crowned Night-heron, Common Buzzard, and Long-eared Owl. We also found that the proportion of Great Tits' second brood has been reduced in recent decades.

Keywords Climate change, Birds, Breeding phenology, Bird ringing, Nestling, Citizen science, Second brood

We live a world where the speed of environmental changes is unprecedented in a geological perspective. The ongoing climate change can exert diverse effects on the birds' habitat, including direct effects like changing temperature and precipitation, and indirect ones like rising of sea levels, increasing risk of fire, disease, and invasion of alien species. These effects induce diverse changes in the life history of bird species. Their geographic range¹ and density² shifts toward the poles, and the timing of spring migration^{3,4} and laying date^{5,6} advances to earlier periods of the year. Therefore, birds' body size, wing, and tail lengths also exhibit slight, continuous changes^{7–9}. Though experimental evidence is lacking, the connections between climate change and birds' phenology and body structure are becoming increasingly visible, strongly suggesting a causal relationship.

Former authors typically explored the advancement of avian breeding seasons by analyzing the point-like events of breeding, like laying dates^{5,6,10,11} or fledging dates¹². Most of these studies cover a few decades (often 30–40 years) and directly link the observed phenological shifts to changes in the local or regional climate^{13–15}. On the contrary, here we follow the approach of the few authors^{16–20} who used the ringing date of nestlings (chicks) as an index of breeding phenology.

The first authors to use the index¹⁶ concluded that “analyses of bird ringing information for millions of offspring of hundreds of bird species deposited in national ringing schemes may provide unlimited access to long-term time series of reproductive variables.” They did not realize, however, all the statistical

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shortcomings arising when working with this type of data. Therefore, for the first time, we give a detailed explanation of the advantages and disadvantages of this approach.

Materials and methods

Bird ringing started in Hungary in 1908. Tragically, all accumulated data were destroyed in World War II when an aerial bomb hit the Institute of Ornithology. Ringing activities started again only in the early 1950s and have been continuous since then²¹, creating a data set available for the period 1951–2020. We preferentially selected species that were ringed from the start of the study period and had large numbers (thousands, or tens of thousands) of nestlings ringed throughout the seven decades. Further, we chose species representing distant phylogenetic clades (different taxonomic orders) and distinct ecological characteristics. Only nine species fulfilled these criteria; the Black-headed Gull *Chroicocephalus ridibundus*, Common Tern *Sterna hirundo*, Black-crowned Night-heron *Nycticorax nycticorax*, Common Buzzard *Buteo buteo*, Long-eared Owl *Asio otus*, Common Kestrel *Falco tinnunculus*, Barn Swallow *Hirundo rustica*, Great Tit *Parus major*, and Eurasian Blue Tit *Cyanistes caeruleus*.

Ringing data were obtained from the Hungarian Bird Ringing Centre, operated by BirdLife Hungary (MME: Hungarian Ornithological and Nature Conservation Society). Several ringers accumulated these data over seven decades, most of whom are/were citizen scientists who had passed a rigorous professional exam to get a license to conduct bird ringing. Only birds identified as ‘pullus’ (nestling, chick) by the ringers were included. The data set referred to the number of nestlings ringed daily for each species. We had no information on whether certain nestlings were nestmates or whether they belonged to the same nest colony. Most of the nestlings were ringed using only the standard ornithological aluminum rings. However, color-ringing schemes have started for some of the species involved in the present study in recent years or decades. The color rings are much larger than the traditional aluminum rings, so they can be read with telescopes, and they are used in parallel with the traditional aluminum rings. Therefore, ringers’ judgments about whether chicks are ripe for ringing are likely to be influenced by using colored rings. Consequently, the introduction of color-ringing schemes might have affected nestling ringing dates. Furthermore, in the present study, color ringing was introduced only for some, but not all, species, which reduces the possibility of comparison between species. Therefore, we excluded all color-ringed nestlings from the analysis to avoid this potential bias and increase the homogeneity of the ringing procedure through the whole period. The number of ringed nestlings and the range of ringing dates (with the color-ringed nestlings excluded) for each species are summarized in Table 1.

Admittedly, ringing dates may make a biased estimate of breeding phenology for several reasons. First, the ringing dates of nestmates represent non-independent statistical data points because ringing all nestmates are coordinated events. However, we have no means to control for these linkages statistically.

Second, similar linkages are potentially caused by the “ringing excursion” phenomenon. This means a ringer who went on a ringing trip likely found several nests on the same day, while no nestlings were ringed on the ‘no-birding’ days. This effect can be particularly potent in colonially breeding birds, where one ringer may handle many clutches at a single colony on the same day. Thus, the emerging ties challenge a central assumption underlying most statistical tests, i.e., the independence of data points. The Black-headed Gull, Common Tern, and Black-crowned Night-heron are colonial breeders in our present samples. Moreover, although territorial breeders, nests of the Great Tit and Eurasian Blue Tit are commonly found in artificial nestbox “colonies” where a similar effect may also arise.

Third, unlike most breeding phenology studies, which give the clutch initiation (first egg laying) date or fledging date with 1-day measurement accuracy, ringing dates provide much less precise indices. Active bird ringers we interviewed estimated that the time window for nestling ringing is about 4–8 days for small-bodied passerines and about two weeks for large-bodied birds like Gulls, Terns, Owls, and Buzzards.

Fourth, sample sizes tend to be much smaller in the early decades of the study period, making our estimates for the early years less reliable.

Finally, ringing dates may exhibit a strange shape of distribution. After the main breeding period in spring or early summer, small passerines often produce a second brood, typically with a smaller number and poorer quality of nestlings²². Further, if the first clutch fails, several birds produce replacement clutches. Thus, the number of broods peaks in the spring or early summer, and then much fewer clutches are distributed through the mid- and

	N	Hatchling ringing period (extreme values)
Black-headed Gull	46,465	110–219
Common Tern	5067	120–238
Black-crowned Night-heron	8935	127–231
Common Buzzard	3650	95–227
Long-eared Owl	3244	28–278
Common Kestrel	18,232	95–243
Barn Swallow	34,385	103–276
Great tit	95,038	49–331
Eurasian Blue Tit	20,233	14–248

Table 1. Number of ringed nestlings (N) and the range of ringing periods (with the color-ringed nestlings excluded). Periods are defined by days numbered from the 1st of January.

even late summer. For these reasons, the distribution of breeding dates tends to be right-skewed. Furthermore, since most ringers were/are non-professional citizen scientists, ringing activities are non-randomly distributed throughout the weekdays but peak every weekend (Fig. 1). The potential bias from weekend peaks is likely stronger for small species, where the nestling ringing period often spans only one (or at most two) weekends, than for larger species, where the nesting period is more extended, spanning two or three weekends.

We applied a two-step analysis strategy to reduce the effects of the above five biases. First, for each year, we took the temporal sequence of conspecific nestlings to identify the median ringing date in the year. This was the day when half of the nestlings had already been ringed that year, to be used as an index of breeding phenology each year. Unlike previous authors who often preferred the mean as an index of breeding phenology, we chose the median because it depends less on the extreme values of the sample, which is advantageous in case of in skewed frequency distributions, as in the present case (see e.g. Figs. 1 and 3). Second, to model how the median ringing dates changed throughout the 70-year study period, we applied a linear regression model using the weighted least squares method (WLS). The model, with year as the independent variable, was fitted for each of the 9 studied species separately.

We used the annual nestling numbers as weights to mitigate the effect of sample size differences between years. The underlying mathematical assumption is that the variance of the estimated median is inversely proportional to the sample size, from which the median is calculated.

Days were numbered from the 1st of January; leap years were considered in the numbering of days (1st of March is the 61st day in leap years, and 60th day in other years).

Results

We have analyzed nine bird species' median nestling ringing dates through a very long study period (1951–2020). Total sample sizes ranged from 3,244 to 95,038 nestlings per species (after all color-ringed birds were removed). Note that samples were not evenly distributed throughout the whole study period. Particularly in the case of Common Buzzard, Long-eared Owl, Common Kestrel, Barn Swallow, and Eurasian Blue Tit, much fewer nestlings were annually ringed during the first 3 decades than during the subsequent 4 decades.

For each of the nine species, results are quantitatively detailed in Table 2 and visualized in Fig. 2. We found that the annual median of ringing dates advanced significantly in the Black-headed Gull, Common Kestrel, Barn Swallow, Great Tit, and Eurasian Blue Tit (by 9, 10, 18, 17, and 14 days, respectively). On the other hand, no significant changes were observed in the median nestling ringing dates of the Common Tern, Black-crowned Night-heron, Common Buzzard, and Long-eared Owl. Nevertheless, even these non-significant shifts went in the same direction (advancement to earlier periods of the year), except for the Long-eared Owl.

Changes in the breeding phenology are not necessarily limited to a simple forward shift along the time axis in small Passerines, where a period of second broods may occur. In our samples, only the Great Tit exhibited a well-defined secondary breeding period in the summer. To illustrate the alteration of Great Tit's reproductive strategy, we arbitrarily divided the study period into two parts: a first period between 1951 and 2000 ($N=20,041$) and a second period between 2001 and 2020 ($N=75,066$). In the second study period, not only did the first and second waves advance to earlier periods of the year, but also the relative weight of the second wave also greatly

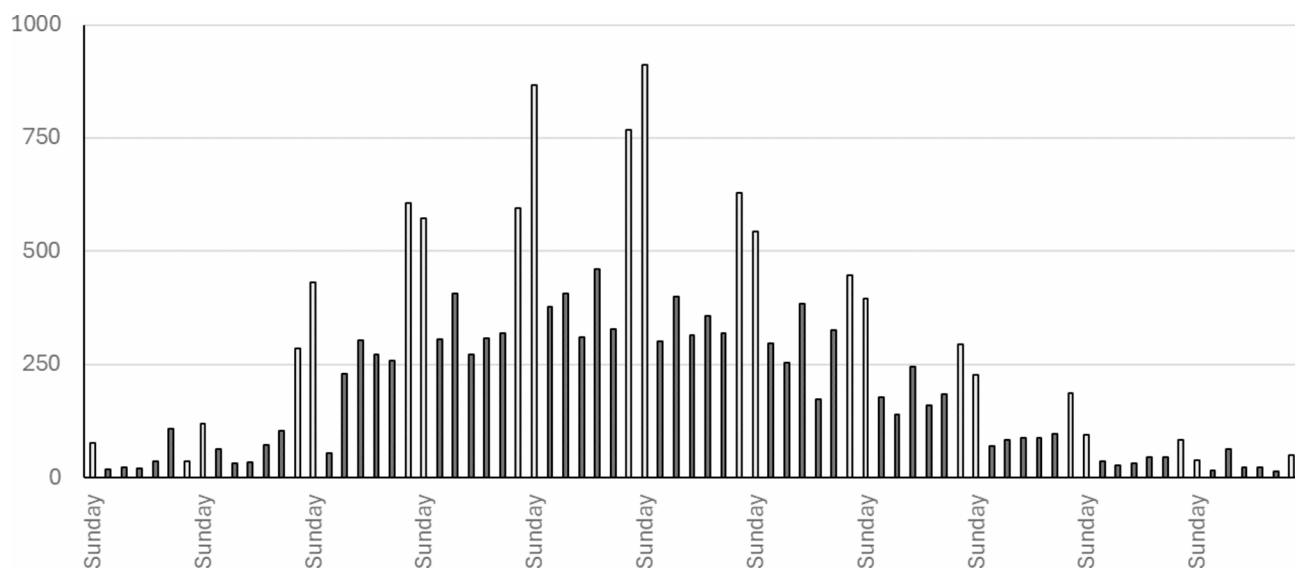


Fig. 1. The daily distribution of ringed Common Kestrel nestlings across weekdays, from 1951 to 2020 ($N=18,232$). Note the slightly right-skewed shape of the distribution with peaks at every weekend. The horizontal axis starts on the 3rd Sunday of May. Saturday and Sunday values (empty bars) are almost always higher than the previous Friday or next Monday values (paired T-test, $t=5.4446$, $df=21$, two-tailed $P<0.0001$).

	Estimate	Std. error	t value	Pr(> t)	DF	Shift (days)
Black-headed Gull	- 0.133	0.050	- 2.687	0.009	63	- 9.3
Common Tern	- 0.089	0.088	- 1.013	0.316	55	- 6.2
Black-crowned Night-heron	- 0.204	0.144	- 1.420	0.161	58	- 14.3
Common Buzzard	- 0.002	0.057	- 0.039	0.969	59	- 0.2
Long-eared Owl	0.023	0.110	0.212	0.833	60	1.6
Common Kestrel	- 0.147	0.051	- 2.875	0.006	62	- 10.3
Barn Swallow	- 0.263	0.072	- 3.663	0.000	66	- 18.4
Great Tit	- 0.245	0.042	- 5.879	0.000	63	- 17.1
Eurasian Blue Tit	- 0.203	0.048	- 4.242	0.000	61	- 14.2

Table 2. Weighted linear regressions models of median nestling ringing dates through a 70-year study period. The annual nestling numbers were used as weights. Note that the significance levels are likely to be overestimated due to the lack of control for the ties among data of nestmates' and colony members. N is the total number of nestlings ringed during the 70 years study period.

decreased. Between 1951 and 2000, 14.5% of nestlings belonged to the second broods, but this proportion was reduced to 11.7% between 2001 and 2020 (Fig. 3).

Discussion

Although a few former authors^{16–20} have already utilized nestling ringing dates to estimate shifts in the birds' breeding phenology, to our knowledge, none provided details about this metric's statistical advantages and disadvantages. Stimulated by this sense of absence, above we summarized the shortcomings of using ringing data for describing breeding season phenologies.

Indeed, the right-skewed shape of distributions with peaks at the weekends, the non-independence of nestmates' data, and the poor accuracy (compared to laying or fledging dates) means that the usual statistical assumptions beyond the analyses are not fully met. However, at least the problems about the shape of the distributions can be eliminated by using the median of ringing date as an index to characterize breeding phenology. Contrarily, however, poor accuracy remains an inherent problem of this method.

A further problem is the linkage between the ringing dates of nestmates and also among colony members. This problem could be solved using a more detailed data series in which the identifier of nests and colonies is registered per chick. However, these data are missing in the old ring logs. Therefore, if we want to examine long-term changes, we must neglect this statistical boundary condition, as we did in the present study. It is unknown how much distortion or inaccuracy this may cause, but it is evidently more pronounced in the case of colonial birds. Taking the Black-crowned Night-heron (a colonial species) in our present data as an extreme example, all chicks were ringed on the same day in specific years (1964, 1968, 1995, 2001) of the study period. These nestlings most probably belonged to the same colony; thus, their ringing dates may not represent statistically independent events.

Neglecting such linkages is a necessary compromise between statistical discipline and fieldwork realities. We argue that it does not affect the expected value of the true breeding phenology (does not cause a directional bias) but reduces the accuracy of the statistical estimation. Consequently, the significance levels provided in Table 2 are likely to be overestimated, and this effect is supposed to be stronger in the case of colonial species (Black-headed Gull, Common Tern, Black-crowned Night-heron), and weaker in the territorial ones.

By accepting and acknowledging this compromise, we may benefit from the greatly extended study periods and much higher sample sizes than other studies based on more frequently used indexes like laying dates and fledging dates. Using this approach, we have documented a significant advancement of the breeding season in five out of nine bird species. The reasons for these differences are not known, because the number of species included is too low to search for influential species traits. However, our results seem to suggest that insectivory may make bird species more susceptible to climate change effects. Our samples involved three species that are strictly insectivorous during the breeding season, Barn Swallow, Great Tit, and Eurasian Blue Tit; their median nestling ringing dates advanced by 18, 17, and 14 days, respectively. The Black-headed Gull and Common Kestrel, both partially insectivorous during the breeding season, exhibited a somewhat weaker change; their median nestling ringing dates advanced by 9 and 10 days, respectively. Changes in the other three species (Common Tern, Black-crowned Night-heron, Common Buzzard, and Long-eared Owl) were not significant, and only the Common Tern is partially insectivorous among them. Breeding phenology was particularly stable through the whole study period in the latter two species, the Common Buzzard and the Long-eared Owl. Both species feed mostly on rodents, a nutrient source which does not change seasonally but typically show longer cycles. Indeed, rodents' non-seasonal population cycles are well-known to affect owls' breeding phenology²³.

The advancement of the appearance of chicks mature for ringing may not only depend on changes in the start of breeding. Other factors, e.g. a reduction in the mortality of early eggs and early chicks may also affect it. Therefore, in a strict sense, the above results do not necessarily prove that the beginning of the breeding season has been shifted earlier. However, in the context of several other, earlier research, this explanation seems most likely. For example, the spring arrival of Common Terns in Germany has been shifted earlier between 1994 and 2020 by 9.3 days²⁴, which is in line with the 6.2 days advancement of nestling ringing that we have experienced (even if this latter change was not significant statistically).

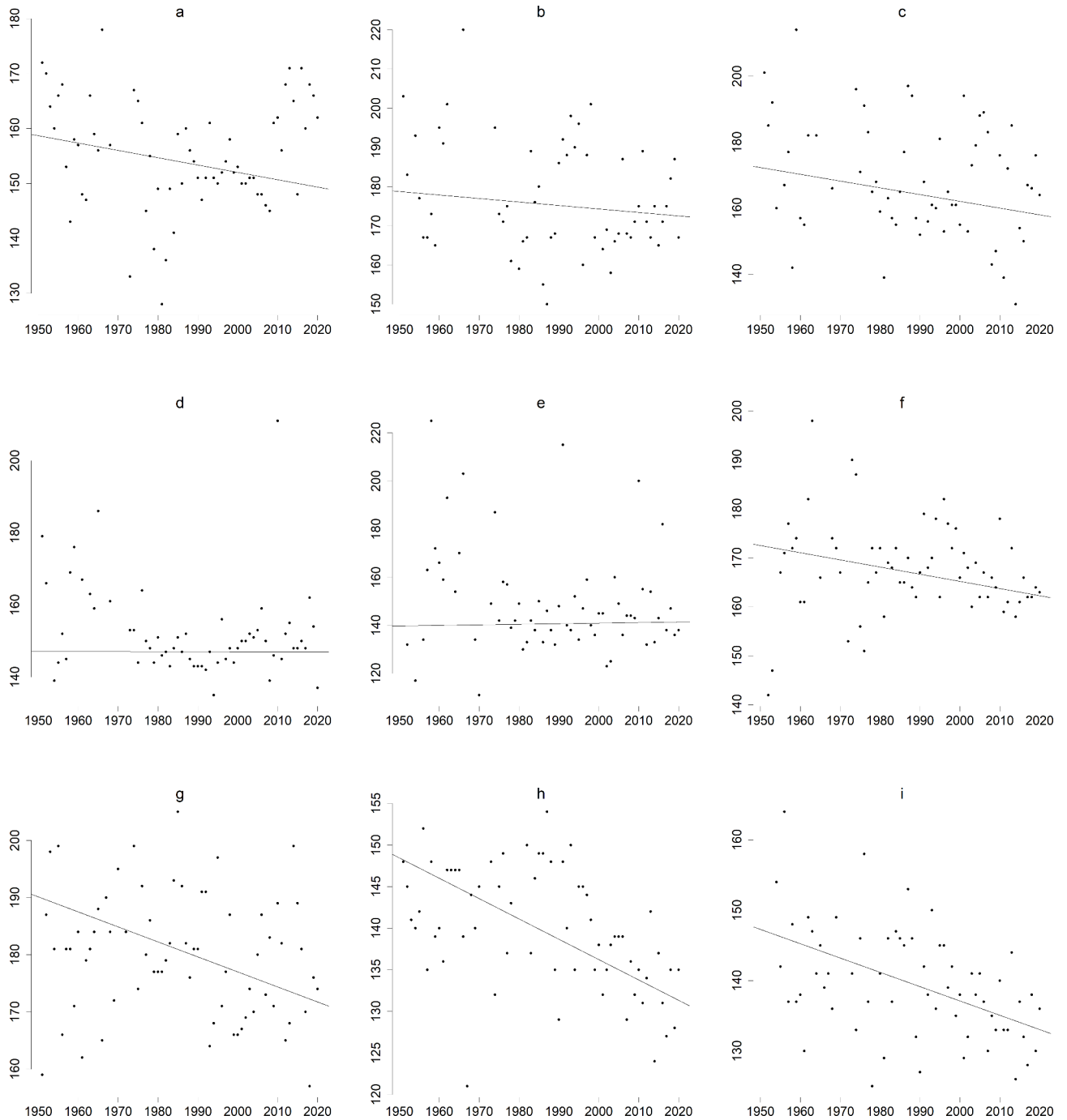


Fig. 2. Weighted linear regressions of median nestling ringing dates through the 70-year study period. Days are numbered from the 1st of January each year. **(a)** Black-headed Gull *Chroicocephalus ridibundus*, **(b)** Common Tern *Sterna hirundo*, **(c)** Black-crowned Night-heron *Nycticorax nycticorax*, **(d)** Common Buzzard *Buteo buteo*, **(e)** Long-eared Owl *Asio otus*, **(f)** Common Kestrel *Falco tinnunculus*, **(g)** Barn Swallow *Hirundo rustica*, **(h)** Great Tit *Parus major*, **(i)** Eurasian Blue Tit *Cyanistes caeruleus*.

Moreover, the co-occurrence of climate change and the forward shift of birds' breeding season does not necessarily prove a direct causality. One cannot exclude the possibility that other unconsidered factors might have also shaped breeding phenology. E.g., Hungary was the first country to ban the pesticide DDT in 1968²⁵, which likely increased the abundance of raptors in the following decades. This is important because predation by sparrowhawks favors early breeding in Great Tits²⁶. Considering such reservations, it still seems likely that climate change caused the forward shift of birds' breeding season in Central Europe. Unfortunately, the primary mechanism by which birds adapt to changing climatic conditions – whether adaptive evolution, phenotypic plasticity, or both – is not known.

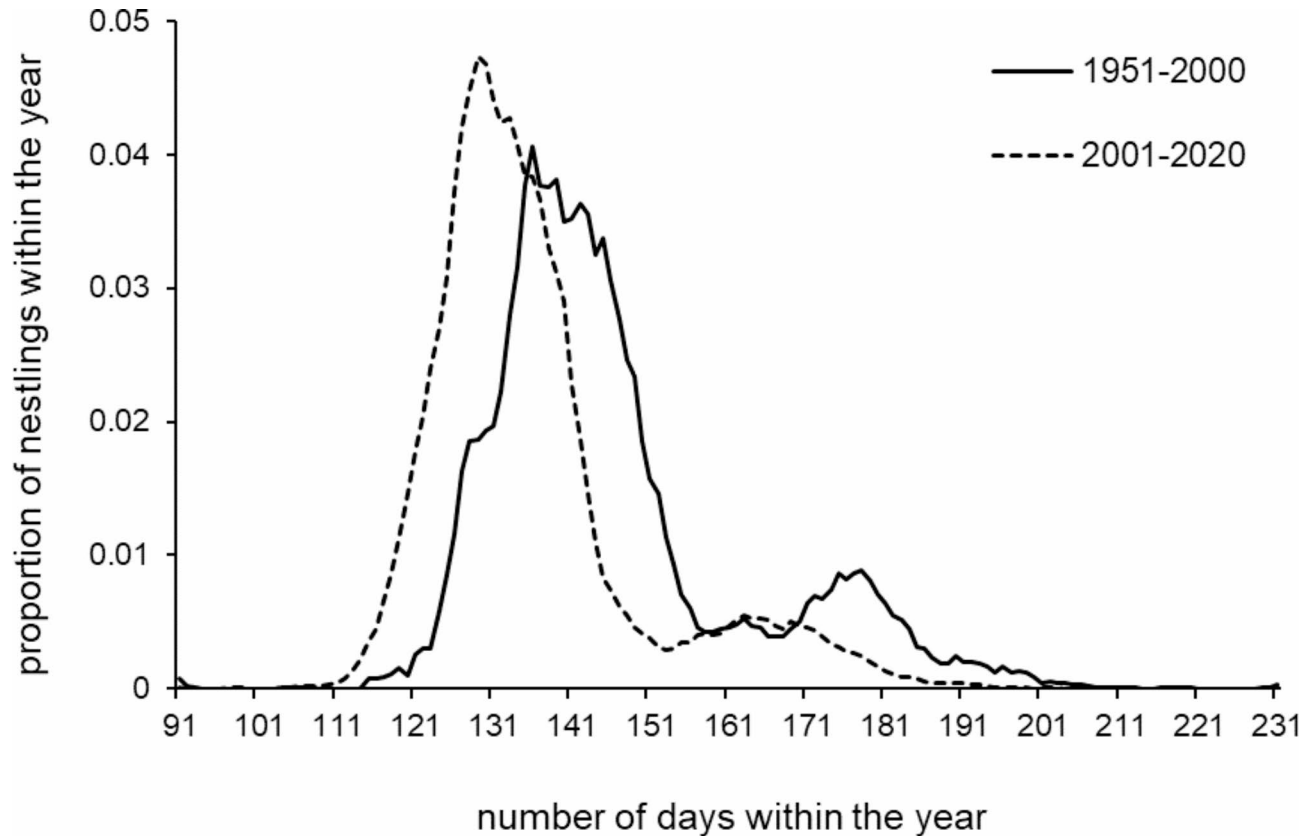


Fig. 3. The frequency distribution of Great Tit nestlings ringed between 1951–2000 and between 2001–2020 (smoothed, 5-day averages). In the latter period, both the first and the second waves advanced to earlier periods of the year. Arbitrary lines of division (arrows) are introduced at the local minimum values between the two waves. Using this line of division, the proportions of the raw numbers of first and second broods differ significantly between the two periods (17131, 2910 and 66285, 8781, respectively). Chi-squared test with Yates correction 116.621, DF = 1, two-tailed $P < 0.0001$.

We also documented an unexpected decrease in the frequency of second broods in the Great Tit, the species with the highest sample size in the present study. We presume that the caterpillars which make up the primary food resource during the breeding period of this species^{22,27} are likely to be decimated by the summers getting hotter and drier, at least in Central Europe. Note that Danish authors¹⁹ documented an opposite effect; the duration of the breeding season increased in species with multiple broods per year. Contrarily, analyzing nestling ringing data of 73 bird species in Finland showed that 31% of species contracted their breeding period, particularly the resident and short distance migrating species²⁰.

Overall, we conclude that analyzing nestling ringing dates provides a suitable method to describe climate-induced long-term changes in avian breeding phenology, although it necessarily requires certain compromises over statistical discipline. This is not necessarily true for species which breed in hardly accessible, large colonies, where the statistical non-independence of data points can be particularly powerful. Insectivorous species considerably advanced their breeding period during the seven decades study period, and the Great Tit also reduced the frequency of second broods.

Data availability

All data on the nestling ringing dates that support the findings of this study are included within this paper and its Supplementary Information file.

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Author contributions

JR and NE supervised the data management and performed the statistical calculations. AS and ABV contributed to all phases of the study. LR designed the study and wrote the main manuscript text. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-76845-5>.

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