

Article

Global Warming as Revealed Through Thirty Years of Analysis on Breeding of Mediterranean Tits

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Abstract: We followed the reproductive parameters of two species of tits, Great and Blue tits, over three decades (1993–2022), in three close habitats of the Mediterranean island of Sicily. We found that they regulated egg-laying dates in the same way, even though they had different dates. The anticipation of laying dates was inversely correlated with the temperature trends of February. The Great tit showed a significant anticipation of laying dates in all three habitats: in the pine woodland, an average anticipation of 19.8 days in 30 years was observed; in the oak woodland, an anticipation of 10.5 days in 30 years was seen; and in the mixed woodland, an anticipation of 13 days in 26 years was seen. The tendency to anticipate the laying date was also observed for the Blue tit in all habitats: in the pine woodland, it significantly anticipated the laying date by 14.4 days in 30 years, while in the oakwood, the anticipation was slightly smaller at 8.7 days in 30 years, and in the mixed woodland, an anticipation of 13.8 days in 26 years was observed. Breeding success did not change over the years for both species. Although we observed through the recoveries of ringed tits a movement of breeding individuals from the pine to the oakwood, we never observed the opposite. This is likely due to the greater availability of feeding resources in the natural woodland. In fact, tits in oak forests feed mainly on caterpillars; in other woodland types, they do not find caterpillars and feed on other arthropods. We hypothesize that most likely in Sicily, these tits, thanks to their phenotypic plasticity, will adapt to the present new conditions resulting from global warming, but if temperatures rise further, they will certainly face difficult times.

Keywords: climate change; *Parus major*; *Cyanistes caeruleus*; Sicily; woodland; laying date; breeding success

Academic Editor: Danilo Russo

Received: 12 December 2024

Revised: 20 January 2025

Accepted: 21 January 2025

Published: 24 January 2025

Citation: Cusimano, C.A.; Chiarello, S.; Massa, B. Global Warming as Revealed Through Thirty Years of Analysis on Breeding of Mediterranean Tits. *Forests* **2025**, *16*, 226. <https://doi.org/10.3390/f16020226>

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1. Introduction

The climate changes we are witnessing are expected to intensify in the coming decades, putting various terrestrial and marine ecosystems at serious risk. According to the 2023 report of the Intergovernmental Panel on Climate Change, the global surface temperature has increased by an average of 1.07 °C over the past 50 years and is projected to increase by 1.5 °C above pre-industrial levels by 2040 due to human activities and emissions of greenhouse gasses and aerosols [1–4]. Climate change means not only higher temperatures but also more frequent extreme weather events (violent storms, heavy rains and floods, and droughts). The different ways in which species modify their physiology and

behavior to adapt to these changes will determine their ability to survive and respond to them [5,6]. The success of breeding birds from different orders can be influenced by different factors (the availability of sufficient food, temperature changes, nesting sites, and predators) [7,8]. Among birds, passerines are the most sensitive species to temperature changes due to their small size, high metabolic rate, and predominantly diurnal habits [9,10–12]. Species that fail to adapt or disperse, moving to other geographic ranges fast enough to counter temperature increases, are seriously threatened [2,3,13,14]. It has been observed that a key response has been to change the timing of reproduction and migration [9].

Tits represent a classic example of climate adaptation, and this is known due to the fact that, as species that breed in natural cavities, they often use nestboxes, allowing for long-term monitoring, such as in Wytham Woods, UK, e.g., [15,16], Hoge Veluwe, Netherlands [17], Sweden (e.g., [4,18–20]), France [21], and the Carpathian Basin [22], which are study areas where data have been available for 3–5 decades or more. The Great and Blue tits are species that occupy a wide range of environments and climates throughout Eurasia, with range margins extending to Eastern Russia, Fenno-Scandinavia, and North Africa, with differentiated populations [23,24], in some cases, recognized as valid species [25].

In recent years, an anticipation of the laying date has been witnessed throughout Europe as a response to warmer spring temperatures (e.g., [16,26–34]) because a precise synchronism with the availability of food resources depends on this. The important adaptation that matches egg hatching with the peak presence of caterpillars is termed the tri-trophic food web (oak bud opening—lepidopteran caterpillars—tits) for chick rearing (e.g., [21,26,30,35–38]).

Although their timing differed in the three different environmental types, the two species investigated over the course of 30 years anticipated the laying date, likely in response to an increase in temperature. The aim of this paper is to highlight the responses of tits to climate change through the analysis of reproductive parameters in a Mediterranean area in deciduous and coniferous woods over a thirty-year period. Our study area lies on an island, generally characterized by a lower number of species and a wider ecological niche of some [39]. This would represent a novelty in comparison with previous studies, mostly carried out in continental areas; the only exception of this long-term island study is that it is carried out in Corsica [21] and concerns only one species (*C. caeruleus*) in natural oakwood, not two cohabiting species (*C. caeruleus* and *Parus major*) in three different habitats (natural oakwood and forest plantation) very close to each other.

2. Materials and Methods

2.1. Study Area

We carried out a study on the Blue tit *Cyanistes caeruleus* (Linnaeus, 1758) and Great tit *Parus major* (Linnaeus, 1758) in three wooded areas differing in tree composition located at a maximum distance of about 2.5 km and a minimum of 0.9 km, consequently at the same latitude (37 °N) and altitude (800–900 m), in Central-Western Sicily, a Mediterranean island, which may represent a special case in terms of both location and its degree of isolation. The study area was in a 1600 ha forest, ca. 600–800 m a.s.l., in the Nature Reserve of Mt. Cammarata (Santo Stefano di Quisquina, province of Agrigento, Sicily, Italy). This forest has three different habitats: (site A) a natural wood area dominated by the deciduous downy oak *Quercus virgiliana* and by the evergreen holm oak *Quercus ilex*; (site B) mixed reforestation (*Pinus halepensis* and *Cedrus atlantica* 55-year-old) since 1996 with silvicultural transformation mixed with broad-leaved trees (*Quercus*, *Fraxinus*, *Acer* and *Ulmus*); and (site C) a 55-year-old pine reforestation of *Pinus halepensis*, *Cupressus sempervirens* and *Cedrus atlantica* (Figure 1).

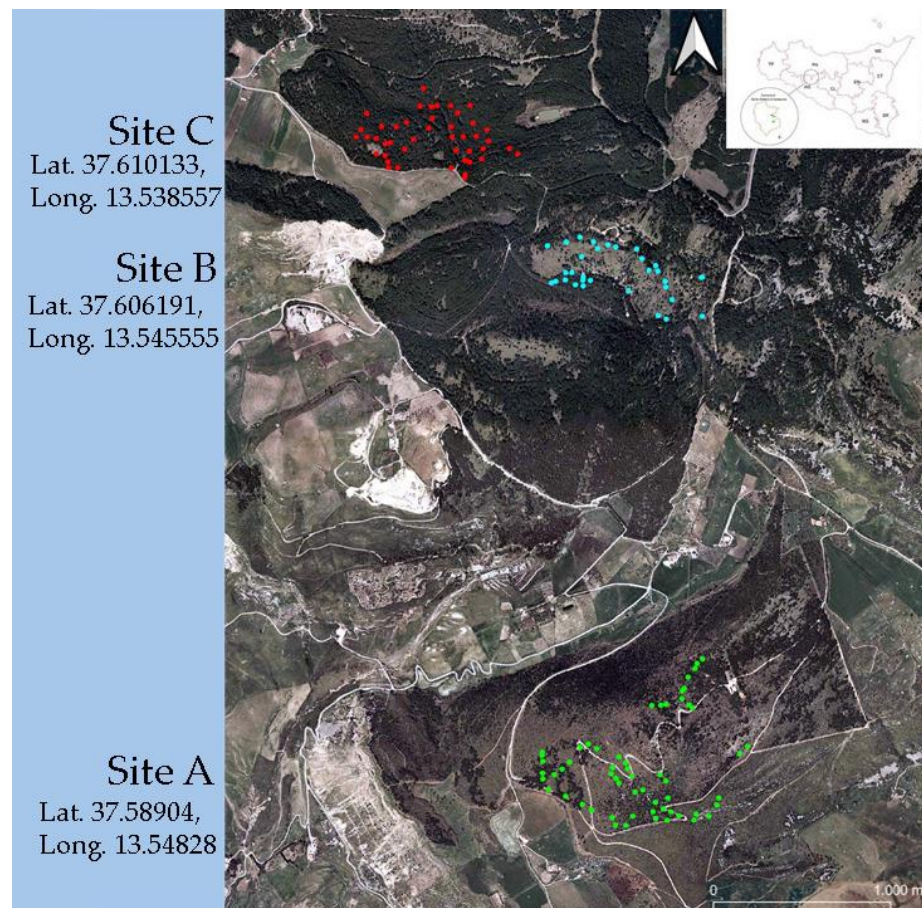


Figure 1. Study area in Sicily (Italy): dots, differently colored, correspond to the position of nestboxes of each site; the vegetation of sites A, B, and C is explained in the text; coordinates can be seen according to the WGC84 system.

2.2. Bird Monitoring

In 1993 (oakwood and pine reforestation) and 1997 (mixed woodland), we placed over 150 nestboxes in such a way that breeding tits territories did not overlap between natural and planted wood plots; the exact position on the nestboxes was measured using a GPS signal (Figure 1). The nestboxes were built from coniferous wood, 1 cm thick, and were placed at 3–4 m above the ground in the dominant trees of each habitat type. They had the following specifications: an entrance hole diameter of 3.4 cm, a chamber size of $15 \times 10.5 \times 15$ cm, and the distance between the lower edge of the entrance hole to the bottom of the nest chamber was 7.8 cm. The nestboxes were equipped with a 5 cm long metal extension to prevent predation by Mustelidae (but see Figure 2 above). Each year, from April to June (1993 to 2022), we visited all nestboxes weekly. We recorded the following: (1) the laying date expressed as the number of days since 1st March, assuming that each female lays one egg per day; (2) clutch size; (3) hatching date; (4) brood size at 10 days; (5) the number of fledglings; and (6) % breeding success (fledglings/No. eggs laid) $\times 100^{-1}$. In order to obtain more accurate results, replacement broods, second broods (occurring sporadically, 1.0% of pairs), and lost broods due to predation (6.4% of nests) by Pine Marten *Martes martes* Linnaeus, 1758, and by the Italian Aesculapian snake *Zamenis lineatus* Camerano, 1981 (Figure 2), were not included in the statistical analysis. All chicks were ringed with ISPRA rings when they were 10 days old. We gathered breeding data on Blue and Great tits over 30 years in oakwood and pine reforestation and over 26 years in mixed reforestation.



Figure 2. Predation by Pine Marten (**above**) and by Italian Aesculapian snake (**below**). Note that the Marten was able to prey on the chicks by dislodging the nestbox and forcing them out, even though the nestboxes were equipped with an anti-predator extension in front of the entry hole.

2.3. Prey Survey

A detailed study of the prey brought to chicks and parents at 8–12 days old was carried out in 1997–2013 on a total of 30 Blue tit broods and 20 Great tit broods in the oakwood, 12 Blue tit broods and 10 Great tits broods in the reforested mixwood, and 25 Blue tit broods and 20 Great tit broods in the reforested pinewood. A light-sensitive video camera (Camera Bird nesting box model CAM20 Handykam, UK) was used to record the activity of chicks and their parents for a minimum of 120 min at each nest, at different times of the day, resulting in the acquisition of a total of 290 h of footage. The video camera was fixed to the nestboxes and connected to a VHS recorder model WI3P LG, South Korea, both powered by 12 V batteries. Prey items were identified from the video footage. Prey-type items were identified from the video recordings (see [31,40]).

2.4. Meteorological Data Collecting

We examined the impact of variations in temperature and precipitation on the laying dates of Great and Blue tits in the area of interest, examining the relationships between the average temperature and precipitation. The climatic parameters taken into consideration for the analyses were the daily temperature and precipitation from 1 February to 31 March; the data were obtained from the Sicilian Region's Water Observatory and, in the case of missing data, were extrapolated from <https://www.wunderground.com/> (accessed on 1 February 2023). The meteorological data were obtained from the nearest weather station, using temperature and precipitation as fixed variables in our models. The preliminary observations of the data indicated a significant and consistent increase in both mean temperatures and precipitation. Subsequently, we developed and applied generalized linear models for each of the two species under study. The spawning date, recorded during the sampling years in each of the three habitats (pine forest, oak forest, and mixed habitats undergoing re-naturalization), was considered as the response variable.

2.5. Statistical Analysis

In total, we analyzed a large sample of data, consisting of 1836 total observations, divided into 728 observations for the Great tit and 1108 for the Blue tit. Analyses were conducted to quantify the variation in breeding parameters (laying date, clutch size, number of chicks fledged, and breeding success) for both the Great tit and Blue tit in relation to years, temperature, and precipitation. Analyses were carried out separately for the following three habitats: pinewood, oakwood, and mixed wood. The aim is to assess the effect of climate change and weather on breeding dynamics.

The laying date was examined by running the generalized linear model (GLM), using the "glm" function of the "stats" package with normal distribution, and the predictors considered were the year, temperature, and precipitation, with habitat included as a fixed effect. GLM with a negative binomial distribution, which is more adequate for count variables, has been used for clutch size and the number of fledglings. Breeding success was analyzed using the Generalized Additive Model for Location Scale and Shape (GAMLSS), using the "gamlss" function of the "gamlss" package, which allows asymmetric distributions to be better modeled, using the "BEINF" family, which is suitable for modeling both values equal to 0 and 1 and values between them. For each model, suitability was verified through residue analysis and Akaike's Information Criterion (AIC). All analyses were conducted with R software, version 4.1.2 [41].

Comparative data were obtained with respect to the frequency that each prey type was delivered to the nestlings by the adults of the two tit species in each of the three habitats. The chi-square test was used to analyze the data to indicate the difference in resource availability in each of the three habitats through testing the differences between prey type and habitats.

3. Results

3.1. Analysis Between Meteorological Data and Laying Date

Models used for temperatures and rainfall in the period 15 February–15 March for the laying date and breeding success of Great and Blue tits in the three habitats produced an inconclusive result. Similarly, in the models used for temperatures in March, the laying date for both Great and Blue tits was not significant in the pine woodland ($p = 0.839$ and $p = 0.986$, respectively) and the mixed woodland ($p = 0.526$ and $p = 0.857$, respectively), and was also highly significant in the oak woodland ($p = 7.58 \times 10^{-9}$ and $p = 2 \times 10^{-16}$, respectively). Also, the effect of temperatures in March on the breeding success, in the case of the Great tit, was not significant in all three habitats (pine woodland: $p = 0.772$; oak

woodland: $p = 0.263$; mixed woodland $p = 0.572$); also, in the case of the Blue tit, it was not significant in all three habitats (pine woodland: $p = 0.0764$; oak woodland: $p = 0.519$; mixed woodland $p = 0.789$).

Concerning instead the effect of February temperatures on the laying date, in the case of the Great tit, it was negative and significant in the pine wood, negative and highly significant in the oak woodland, and non-significant in the mixed woodland. In this case, the Blue tit was negative and significant in all three habitats. Analyses conducted with the mean rainfall data in February show that the Great tit has a tendency to anticipate the laying date significantly in the mixed woodland and pine forest ($y = -0.024$, $p = 0.009$, and $y = -0.026$, $p = 0.005$, respectively), but not in the oak forest ($p = 0.79$); for Blue tits, however, no statistical significance was found in any of the three habitats studied (Table 1, where data on the breeding success are also reported).

Table 1. Summary of GLM and GAMLSS model analyses for February mean temperatures, respectively, with the laying date and breeding success of Great and Blue tits. * = 0.05; ** = 0.01; *** = 0.001.

Mean Temperature February	Habitat	<i>Parus major</i>		<i>Cyanistes caeruleus</i>	
		Estimate	<i>p</i>	Estimate	<i>p</i>
Laying date	Pine Wood	-0.764	0.05 *	-0.825	0.005 **
	Oak Wood	-1.113	3×10^{-7} ***	-1.811	2×10^{-16} ***
	Mixed Wood	0.707	0.0704	-0.725	0.008 **
Breeding success	Pine Wood	0.052	0.359	-0.018	0.64935
	Oak Wood	-0.032	0.341	-0.017	0.529
	Mixed Wood	0.04	0.3916	0.009	0.84663

Thus, the model that we considered reasonable was that between the laying date and the mean temperature in February, a negative and significant tendency was evident for the Great tit, indicating anticipation of the laying date in the pine woodland ($y = -0.764$, $p = 0.05$) and in the oakwood ($y = -1.113$, $p = 3 \times 10^{-7}$); this is in contrast to the mixed woodland, where the tendency is slightly positive ($y = 0.707$), but not statistically significant. As far as the Blue tit is concerned, in all three habitats, there is a significant tendency to anticipate the laying date; in the oak woodland, there is a significant tendency to anticipate the laying date ($y = -1.811$, $p = 2 \times 10^{-16}$), as well as in the pine woodland and in the mixed woodland ($y = -0.825$, $p = 0.005$, and $y = -0.725$, $p = 0.008$, respectively).

3.2. Breeding Parameters of Tits Through 30 Years

The GLM models for the Great tit show a significant anticipation of the laying date over the years in all three habitats. In the pine woodland, significant anticipation of the laying date was observed, with a mean of 0.66 d yr^{-1} ($p = 5.43 \times 10^{-13}$), which was 19.8 days in 30 years. Similar anticipations were also observed in the oakwood and in the mixed woodland, with 0.35 d yr^{-1} ($p = 2.01 \times 10^{-12}$; 10.5 days in 30 years) and 0.5 d yr^{-1} ($p = 7.24 \times 10^{-7}$; 13 days in 26 years), respectively.

For the Blue tit, the tendency to anticipate the laying date was confirmed in all the habitats examined. In the pine woodland, it anticipated laying by a mean of 0.48 d yr^{-1} ($p = 7.79 \times 10^{-9}$), which is 14.4 days in 30 years, while in the oakwood, the anticipation was slightly smaller, with an average anticipation of 0.29 d yr^{-1} ($p = 2.69 \times 10^{-12}$), which is 8.7 days in 30 years. In the mixed woodland, the average 0.53 d yr^{-1} ($p = 1.249 \times 10^{-10}$) was detected to be 13.8 days in 26 years (Tables 2 and 3, Figure 3).

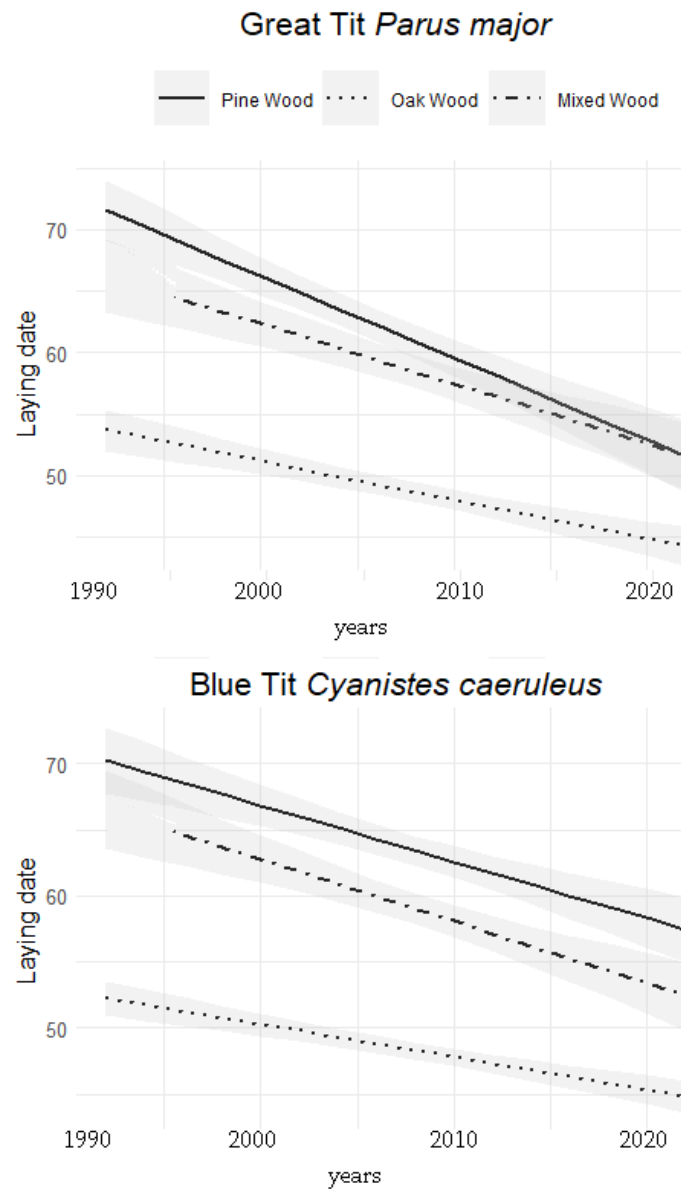


Figure 3. The thirty-year trend of the laying date for Great and Blue tits in the Sicilian study area. Laying date: days from 1st March.

Table 2. Present breeding parameters of Great and Blue tits in the three habitats of the Sicilian study area. Laying date: days from 1 March.

Species	Habitat	Laying Date			Clutch Size			N° of Fledglings			Breeding Success (%)
		Mean	s.d.	n.	Mean	s.d	n.	Mean	s.d	n.	
<i>C. caeruleus</i>	Pine wood	63.6	6.5	228	6.5	1.3	228	3.4	2.3	171	52.8
	Oak wood	49.1	6.8	682	8.5	1.6	682	6.1	3.1	560	71.4
	Mixed wood	58.7	1.9	212	7.7	0.6	211	5.0	1.1	145	64.7
<i>P. major</i>	Pine wood	62.0	5.4	168	6.3	1.4	157	3.6	2.4	109	56.6
	Oak wood	49.4	5.8	422	8.2	1.5	421	5.9	2.9	354	72.2
	Mixed wood	58.3	3.5	151	6.8	0.9	151	4.5	1.1	109	65.8

Table 3. Laying date anticipation of Great and Blue tits in the three habitats of the Sicilian study area over three decades.

Species	Great Tit <i>Parus major</i>	Blue Tit <i>Cyanistes caeruleus</i>
Laying anticipation in oakwood (days/30 years)	10.5	8.7
Laying anticipation in pine reforestation (days/30 years)	19.8	14.4
Laying anticipation in mixed woodland (days/26 years)	13.0	13.8

3.3. Breeding Success

Of 1837 total observations, 117 cases of nest predation and 19 s clutches occurred, and these data were excluded from statistical processing. The analysis of breeding success revealed that, in general, there was no significant effect of year on reproductive success in any of the habitats under study for either species. However, some patterns emerged in relation to the variability and distribution of reproductive success. In particular, for the Great tit, the parameters relating to the dispersal and distribution of the response were significant, suggesting that factors not directly linked to the year may influence the variability of breeding success. Also, for the Blue tit, the models showed considerable variability in the distribution of breeding success (indicated by the sigma and nu values, respectively, with the dispersion parameter describing the variance in the data around the mean and skewness parameters describing the shape of the distribution), particularly for pine and mixed woodlands. With regard to the average precipitation in February, there was no significant effect on breeding success, except for Blue tits in the oak forest ($y = 0.001$, $p = 0.0001$).

3.4. Prey Delivered to Nestlings

The food intake per nestling was higher in the oakwood than in the reforested habitats due to greater food availability, and consequently, both Blue and Great tit nestlings grew faster. In the first ten days after hatching, Blue tit nestlings grew 0.89 ± 0.28 g/day in the oakwood, 0.87 ± 0.38 g/day in the mixed wood, and 0.79 ± 0.86 g/day in the pine wood, while Great tit nestlings grew 1.44 ± 0.43 g/day in the oakwood, 1.43 ± 0.53 g/day in the mixed wood and 1.37 ± 1.23 g/day in the pine wood. This increased rate of growth allowed the oakwood nestlings to fledge at least one day earlier than nestlings in the reforested habitats. In addition, the nestlings in the reforested mixed woodland grew faster than nestlings in the reforested pine woodland. Caterpillars comprised the primary prey resource that was fed to Blue and Great tit nestlings in the oak and mixed woodlands, with a much lower frequency in the pine reforestation area (Figure 4). The prey delivered to the nestlings was more diverse in the pine reforestation area, mainly for Great tits; Blue tits carried fly adults and larvae, spiders, scale insects, beetle larvae, moths, and centipedes, and Great tits delivered spiders and fly larvae, in addition to other arthropods (Figure 4).

The prey in each of the three woodlands was found to be significantly different, with the chi-square test being highly significant for both species (Great tit, $\chi^2_{12} = 260.10$, $p < 0.0001$; Blue tit, $\chi^2_{12} = 656.14$, $p < 0.001$).

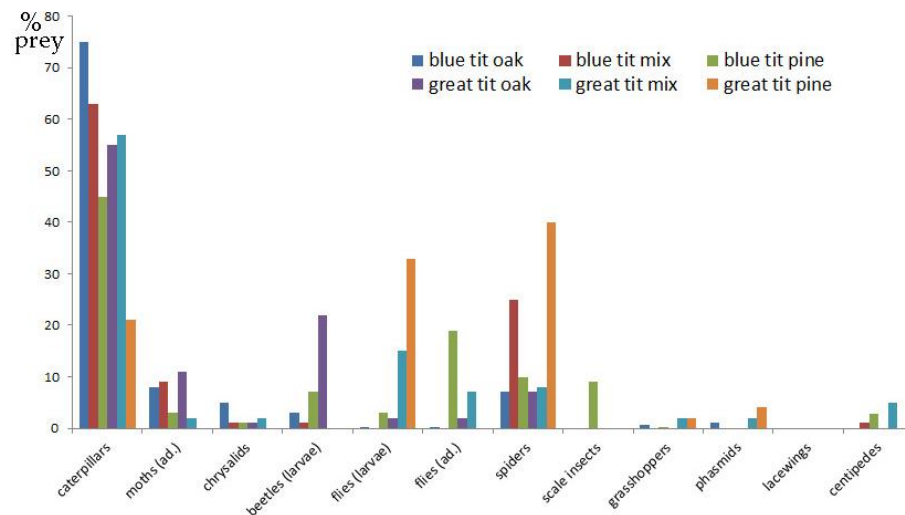


Figure 4. The percentage of prey carried by parents to chicks in 67 nests of Blue tits and 60 nests of Great tits monitored by video camera for the three habitats investigated.

4. Discussion

4.1. Advancement of Egg-Laying Date in the Three Habitats

Following Visser et al. [28], spring temperatures in temperate regions have increased over the previous 20 years, and many organisms have responded to this increase by advancing their time of reproduction. Compared to the date of publication of Visser et al. [28], now the increase in temperatures has continued for more than 40 years, and our data collected in three decades on a Mediterranean island are certainly a good starting point to make some considerations.

In accordance with Kvist et al. [42], Great tits survived the last glacial period in a single isolated refuge, probably in the Mediterranean Sea, after which they rapidly colonized the European continent, and the population grew. Lemoine et al. [43] analyzed 884 individuals from 30 sites across Europe and found a low but significant genetic differentiation among sites; genetic differentiation was higher, and genetic diversity was lower in South-Western Europe. They explained these regional differences by winter temperature, assuming that this might have important implications for the evolution of sub-populations, mainly if we consider climate change. Gładalski et al. [44], examining the laying dates of Blue and Great tits in Poland (in parkland and forest) in 2013 (the coldest spring in 40 years) and 2014 (the warmest spring in 40 years), found that a rather large extent of breeding plasticity developed in reaction to challenges of irregular inter-annual variability in climatic conditions, and considered such plasticity sufficient for these tits to adjust the timing of their breeding to the upcoming climate changes. Stonehouse et al. [45] have suggested that geographical climate adaptation has been occurring since Great tits left their Southern European refugia at the end of the last ice age and found evidence that they have adapted over historical time to different climates through numerous evolutionary changes. Therefore, they have shown that there is a substantial climate-associated genetic variation in the Great tit, which will be essential for adaptation to future changes. We can assume that Blue tits also have an origin in Southern Europe (e.g., [21,25,46]) and will adapt to climate change. Optimal phenology is crucial for population persistence ([47], but see references [4,16,20,48] on four species of tits in Sweden, Coal tit *Periparus ater* (Linnaeus, 1758), Crested tit *Lophophanes cristatus* (Linnaeus, 1758), Marsh tit *Poecile palustris* (Linnaeus, 1758), and Willow tit *Poecile montanus* (Conrad, 1827), where interannual variations in population mismatch have not affected population growth). However, the process of global warming may cause directional selection for a general reduction in the basal metabolic rate, affecting

the general life-history strategy at the population level [49]. The breeding success of birds involves many factors, such as predators, microhabitats, insularity, and so on.

Some authors have demonstrated that local weather parameters, such as rainfall and air temperature, may correlate with the advancement of reproduction in birds (e.g., [50,51]). In a Spanish orange grove, the increase in temperatures in March between 1986 and 2019 was related to an advancement in the breeding season [52]. As an indicator of thermal conditions for tits, Gładalski et al. [44] used pre-laying, early-laying warmth summaries of the daily maximum temperatures between 15 March and 15 April each year (see also [53–55]). According to Laczi et al. [22], the laying date of tits in the Carpathian Basin was negatively related to January–March temperatures. In our study, the laying date of tits was negatively correlated with February temperatures; our overall breeding data show a general trend towards earlier laying in both species over the study years, with some variation depending on habitat, suggesting temperate adaptation to environmental changes. Because temperatures have risen over the past few decades, the laying date has been brought forward.

However, in all Palaearctic countries, the laying anticipation is the same; for example, Barba Campos [56] found that the Great tit starts laying later as the latitude increases (26 European populations included), and the mean clutch size increases significantly as the latitude increases (46 populations included). Mainwaring et al. [57], in a study on latitudinal variations in Blue and Great tits, found that the mean first egg date of both species was regulated by decreasing latitude and increasing spring temperatures, although the clutch size and brood size at hatching and fledging did not vary (see also [58]). Not all tit populations responded the same way to ambient temperature changes, with Mediterranean birds being sensitive to the ambient temperature [59]. Møller et al. [60] examined the relationship between temperature and the coexistence of Great and Blue tits breeding in 75 study plots across Europe and North Africa. As expected, as the spring temperature increases, the laying date advances, and as winter temperature increases, clutch size is reduced in both species. However, in our case, we observed a positive and highly significant increase in clutch size in the mixed woodland only for Blue tits ($y = 0.078$, $p = 9.65 \times 10^{-5}$) and a negative and significant decrease in the number of fledglings over 30 years in both tits only in the oakwood (Great tit, $y = -0.089$, $p = 3.92 \times 10^{-6}$; Blue tit, $y = -0.095$, $p = 1.71 \times 10^{-9}$). Since birds generally calibrate the number of eggs laid according to the available food resources, it is likely that the increase in clutch size for Blue tits in mixed woodland and the decrease in the number of fledglings of both tit species in oakwood depends precisely on the different resource availability in the two habitats. In fact, the mixed forest is a changing habitat and, therefore, also has progressive dynamism from a resource perspective, while the oakwood is a natural wood that has been stabilized for many years; resources in oakwoods are more likely to be constant but did not always match the hatching date.

4.2. Matching Breeding Parameters of Blue and Great Tits in the Three Habitats

According to Blondel et al. [21], the response of Mediterranean Blue tits to spatial habitat heterogeneity depends on their range of dispersal relative to the size of habitat patches. The authors consider that dispersal over short distances leads to local specialization, whereas dispersal over long distances leads to phenotypic plasticity. Gene flow between habitats of different quality may produce local maladaptation and a source–sink population structure, but generally, gene flow lowers genetic divergence and impedes local adaptation between populations [43]. In our study, also in the Mediterranean area, the dispersal of young individuals occurred within a limited area over short distances, and local specialization may likely depend on the different forms of resource availability; this

also has been noticed for Great tits in a Spanish orange grove, where dispersal resulted in very modest outcomes [61].

The coexistence between Great and Blue tits, and sometimes other hole-nesting birds, constitutes a classic example of species co-occurrence resulting in potential competitive interference for food and breeding and roosting sites [62]. Källander et al. [32] showed the advancement of laying dates in three species of tits (Paridae) in southernmost Sweden over recent decades, considering that their results could reflect ongoing microevolution favoring earlier laying times but could also be a result of other factors such as increased intra- or inter-specific competition for early breeding. Møller et al. [61] found evidence for the effect of the intraspecific competition of Blue tit laying dates (later laying at a higher density) and clutch sizes (smaller clutch sizes at higher density) but no evidence of significant effects of intraspecific competition in Great tits, nor effects of interspecific competition for either species. If interspecific competition occurs, a reduction in the mean and an increase in variance in the clutch size in Great and Blue tits can be predicted when the density of heterospecifics is higher than the density of conspecifics, and for intraspecific competition, this reduction can occur when the density of conspecifics is higher than the density of heterospecifics. Interestingly, in the Sicilian study area, we previously observed that the onset of breeding of the two species of tits coincided almost perfectly [31], and presently, we may confirm this; the timing of breeding over the three decades is also very similar for the two species in the three habitats, even if it is different in each habitat (cf. Table 2). Altogether, we may exclude any possible competitive interferences between the two species of tits in our study area; some pairs (about 10%) occupied the same nestbox or the same area for several consecutive years, showing high fidelity to the breeding site.

Andreasson et al. [34] used the laying date and environmental data from 39 years (1983–2021) to determine how climate change affects laying date variations in Blue tits and Marsh tits *Poecile palustris*. Both species advanced their mean laying date (0.19–0.24 d yr⁻¹, that is, between 7.41 and 9.36 days in 39 years), which, in turn, showed a negative relationship with maximum spring temperatures in both Blue and Marsh tits. In spring, with no clear temperature increase during the time window in which the mean laying date was most sensitive to temperature, the start of breeding in Blue tits was distributed over a longer part of the season. Their findings suggest that temperature change can shape the variation in breeding phenology in a species-specific manner, possibly linked to variations in life-history strategies. In our study area, we found a similar anticipation of the laying date only in oakwoods, which are the only natural woodland where we worked; in the other habitats (pine reforestation and mixed woodland), both planted by man, the anticipation of the laying date of both tits was higher (cf. Table 3), and this is possibly due to a greater anticipation of feeding resources with respect to the natural wood. In addition, we did not find any year of breeding distributed over a longer part of the season (asynchronous breeding), which is a phenomenon that occurs regularly in Pantelleria island (between Sicily and Tunisia), where the African Blue tit *Cyanistes ultramarinus* (Bonaparte, 1841) lives, and has a very asynchronous breeding season and also very poor breeding success (4.4–4.5 fledglings) [63]. However, Adamou et al. [64] found out that in Algeria, Great tits and African Blue tits start laying relatively late, considering the latitude of the area, even in late May, which is likely to be associated with harsher climatic conditions and the delayed availability of food resources.

We believe that one of the most important aspects that has regulated the breeding of these two tits species over the past three decades is the availability of food resources. In the oakwood, where there is a high availability of caterpillars, the tits lay more eggs and fledge more chicks. In fact, while there have been some movements of pairs from reforestation to oakwood, but the opposite movement has not occurred.

4.3. Importance of Caterpillars in the Oakwood

In a Mediterranean oakwood, Ceia et al. [65] demonstrated the high importance of caterpillars in the nestling diets of Blue tits, Great tits, and Nuthatch *Sitta europaea* Linnaeus, 1758, and suggested their complementary predation on early and late instars of the same Lepidoptera species. Previously, van Balen [17] showed that prey density on coniferous trees is considerably lower than on broad-leaved trees. Barba Campos [56] found in a Spanish orange grove that the laying dates and clutch size of the Great tit were related to the phenology of moths while breeding success was related to moth abundance. Massa et al. [31] highlighted the difference in the food intake brought to chicks by adults of Great and Blue tits in the oakwood (mainly caterpillars), pine reforestation, and mixed woodland (very few caterpillars and many other arthropods, such as spiders) despite the considerable proximity of the three areas studied. Garrido-Bautista et al. [66] also found that clutch size and the number of fledglings of Blue tits were highest in the Pyrenean Oak forest and lowest in the coniferous Scots Pine, likely depending on lower resource availability.

The importance of caterpillars for tits may depend on the high quality of this food; in fact, sodium is present in modest amounts in all arthropods, but only lepidopteran caterpillars have high values of potassium, which is an important element for the functioning of the sodium–potassium pump, the active transport of which is one of the most energy-consuming processes in the body and probably accounts for most basal metabolism. The more active the cellular pump is, the more ATP, the body's main energetic source, is formed [31]; this is very important because tits have a high basal metabolic rate.

Both et al. [30], in a long-term study, showed that between 1988 and 2005, budburst advanced (not significantly) with 0.17 d yr^{-1} , while between 1985 and 2005, both caterpillars (0.75 d year^{-1}) and the hatching date of the passerine species (the range of four species: $0.36\text{--}0.50 \text{ d year}^{-1}$) advanced. Laczi et al. [22] have found that the date of peak abundance of caterpillars is negatively associated with local temperatures in December–January, while the laying date is negatively related to January–March temperatures. They have found that the date of caterpillar peak abundance and the laying date of Great tits has advanced, while in Blue tits, clutch size decreased over the decades, but the laying date did not advance. Also, they suggest that weather conditions during the months that preceded the breeding season, as well as temporally more distant winter conditions, are connected to breeding dates. Their results highlight that phenological synchronization and food availability is different between the two tit species; namely, it was disrupted in Blue tits only. Our results allow us to establish that in the Sicilian study area, there is no difference in the synchronization of the food availability and breeding phenology of Great and Blue tits, likely because their prey in the three woodlands resulted in differences (cf. Figure 3). Thus, we may assume that there is no competitive interference between these two species of tits.

Shiao et al. [67] found that early-brood nestlings in the broadleaf habitat were heavier than those in the coniferous habitat. However, the between-habitat difference disappeared in the late broods because the mass of nestlings in the coniferous habitat increased significantly. We may confirm that nestlings in our oakwood study were more precocious than those of the pine and mixed woodlands and fledged one day earlier than the others.

Finally, one aspect that should be given due consideration is the fact that our data were obtained on the woods of an island; it is well known that islands are home to fewer species than the continent, and consequently, the ecological niche of each species is wider than the respective species living in continental areas (e.g., [68]). This has ecological effects of some importance, such as trophic resources during reproduction, lower interspecific competitive interactions, and so on. Locally, some tits adapt to very particular conditions; we cite the case of the African Blue tit, which in North Africa occupies non-forested habitats and can even be found inside oases, where it breeds on date palms [64].

In our study, we did not find interspecific competitive interference between Great and Blue tits, which may breed very close with matching times obtaining more or less the same breeding success. Following the other authors who worked on this research subject, there were differences in the behavior of tits depending on the habitat, resource availability, latitude, and also on the co-occurrence of other tit species. However, in accordance with Huang et al. [69], climate change has desynchronized insect and vegetation phenologies across Europe; they examined the differences in the occurrence dates of 1584 herbivorous insects across four orders and the corresponding dates of leaf unfolding, finding that 61.2% of the vegetation and insect phenologies have become highly asynchronous, with vegetation phenology advancing four-fold faster than insect phenology. Considering the high number of variables, such as latitude, resources, habitat quality, and the number of insectivorous species living in the habitat, it is impossible to make a general prediction for the future of the two tits species we have studied, but we can say that most likely in Sicily these birds, thanks to their phenotypic plasticity, will adapt to the new conditions resulting from global warming. However, even though breeding success has not changed over the past few years for both species, the increase in clutch size for the Blue tit in mixed woodland and the decrease in the number of fledglings of both tit species in oakwood likely may depend on different temporal resource availability in the two habitats, most likely not matching with the hatching date. This does not allow us to be comfortable about the future of these birds if temperatures, as predicted by the IPCC [1], continue to rise.

Overall, we believe that our data, while demonstrating gradual adaptation to the new conditions caused by climate change, cannot be considered a generalizable model for the entire Mediterranean area and most likely cannot even be considered generalizable to other Mediterranean islands. Of the Mediterranean islands, tit breeding data are only available from the following: (1) Corsica, e.g., [70], wherein two sites 25 km apart, respectively, characterized by deciduous and evergreen oakwoods, Blue tits differed markedly in their breeding traits, and the differences were genetically based; (2) Cyprus [71], where the start of the breeding season of the Great tit is considerably earlier compared to other Mediterranean regions. Thus, it is possible that the environmental conditions of each island are the key components that influence the reproduction of birds and, in particular, forest species, such as tits.

5. Conclusions

It is now accepted by the scientific world that temperatures are rising at an unprecedented rate, so there is an urgent need to understand how organisms are adapting to climate change [45]. We followed the reproductive parameters of two species of tits over three decades in three close habitats of the largest Mediterranean island, finding that both species advanced their egg-laying date in the same way, even though different dates were observed in the three habitats. The anticipation of laying dates was inversely correlated with the temperature trends in February, but this could also be linked to the feeding resources of the three habitats. Breeding success has not changed over the years for both species; tits in oak forests feed mainly on caterpillars, whereas in other woodland types, they do not find caterpillars and prey upon other arthropods. Although we have observed through the recoveries of ringed tits a movement of breeding individuals from pine reforestation to oakwood, we have never observed the opposite. This is likely due to the greater availability of feeding resources in the natural woodland and shows the presence of a frequent gene flow between tits breeding in our different study habitats.

It has been hypothesized that regular increases in winter temperatures, particularly in the Mediterranean area, could cause some dangerous situations during breeding times when the birth of chicks does not match the maximum availability of resources (insects). However, according to Vedder et al. [47], under climate change scenarios, the two major

mechanisms by which organisms can adapt to changing local conditions are adaptive evolution and phenotypic plasticity; see [72]. Therefore, they suggest that thanks to the phenotypic plasticity of tits, there is little risk of population extinction under local temperature increases. Also, Marrot et al. [46] confirmed the general assumption that recent climate change translates into strong selection favoring earlier breeders in Blue tits and that differences in fitness among individuals varying in their breeding phenology increase with climate warming; the climate influence on the selection acting on the laying date could favor an adaptive response in this trait since it is heritable.

Author Contributions: Conceptualization, methodology, validation, formal analysis, investigation, writing—original draft preparation, review and editing—all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Regional Administrations and the ISPRA issued permits to ring tits: Bruno Massa (ringing permits no. 553/13 and 2452/1).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Acknowledgments: We thank the Azienda Foreste Demaniali Regione Siciliana and the Distaccamento Forestale of Santo Stefano di Quisquina for assistance and research permits, and the Servizio Informativo Agrometeorologico Regione Siciliana (SIAS) for meteorological data. We are grateful to Beniamino Margagliotta for his collaboration and sharing some data. We are very indebted to three anonymous referees, who considerably improved the first version of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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