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CLIMATE-DRIVEN BREEDING SHIFTS IN MIGRATORY BIRDS: A 20-YEAR FIELD STUDY

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Abstract

In the past two decades, the population of migratory birds has shifted significantly, in regard to their reproduction timing. This is largely due to the fact that the climate change is increasingly taking place. This was a 20 years, field trial that observed >12 species encompassing numerous flyways and their arrival dates, nesting early commence dates as well as clutch sizes and fledging success, to understand the impacts of the local climatic changes in terms of temperature, rainfall, and growing degree days. We found that, long-term data indicated that the first eggs were occurring earlier at a rate of 6.3 days per decade. It was directly associated with the beginning of spring temperatures ($r = 0.78$, $p < 0.01$). Clutch size and hatching success simultaneously decreased significantly (though not by much on average) in species that breed higher latitudes. This implies that the latter is out of synch with regard to the time of the breeding and the prime food availability. The most committed phenological practitioners to not alter, namely long distance migrants, were in the worst position to accommodate changing phenology. According to satellite-based NDVI and habitat evaluation, importantly, fledging rates were reduced in association with inferior plant productivity of breeding spots. Such findings indicate that the ecology of bird mating is Modifying largely due to both the direct thermal information and the indirect trophic dynamics. This paper is made up of a mixture of ecological modelling, field based phenology and the perception of the stakeholders to provide us with an insight as to the level of migratory birds approachability to adapt to changing climatic environments as well as their scarcity. According to our findings, it is necessary to take steps to preserve vulnerable species since we have to establish a conservation strategy based on climate projections as well as phenological limits.

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INTRODUCTION

The migratory birds are birds with long and difficult journeys as they move seasons. Their breeding behaviours are also intricate and to a large extent sensitive to environmental changes. Such are critical life events as the selection of a nest site, initiation of a clutch, and chick rearing which are rather vulnerable to weather conditions (Kevan et al., 2024). One should also know how the phenological changes in these birds, particularly the changes of the climate, will influence their populations and how to preserve them (McPherson et al., 2025). The rate at which the globe has warmed up in the past few decades is unprecedented and this has had massive implications on natural ecosystems and disrupted the ecosystem dynamic between migrating birds and their nesting places (Jain, 2023). This paper examines the influence of climate change on the timing and success of nesting of migratory birds population. It works with a comprehensive 20-year field data and identifies the long-term patterns and processes. This huge dataset allows us to conduct an extensive analysis of the connection between change in breeding phenology and change in environmental parameters, such as temperature and precipitation. This would tell us how well these species are able to adapt to change in the climate (Andrew & Fox, 2020). According to this study, the selective pressure faced by migratory birds due to the increasing temperatures on Earth is significant, which might contribute to their more frequent extinctions because they are bound to alter their breeding periods (Duffy et al., 2022). Such changes might lead to the availability of resources at an inappropriate time, which might influence breeding outcomes and the entire population health (Mathes et al., 2021). Due to the close linkage of climate change and bird phenology, we should pay specific attention to the role of both direct and indirect impacts of climate on breeding success (Tillotson et al., 2021). This research aims at providing application-related examples in the field that can support the linkage of specific weather conditions to mating phenology of birds. This will enable us to understand more on the impact of climate change on biodiversity. It is also necessary to know how these changes vary over time and space due to the fact that it is not possible to have a fixed distribution of species; species distributions are always dynamic, more than with species that do not move frequently, like migratory birds (Andrew & Fox, 2020).The extensive data provides the opportunity to perform an in-depth analysis covering the relationship between changes in breeding phenology and changes in such environmental conditions as temperature and precipitation. This will provide us with data on adapting capabilities of these species to a changing climate. This research asserts that the global warming is associated with much selective pressure exerted on migratory birds which leads to shifts in their reproductive cycles that may increase their risks of extinction (Andrew & Fox, 2020). Such types of changes also have a capacity to make resources ready at the incorrect moment, and this could impact the breeding success and the well being of the entire population. Reproductive success of migratory birds will be considered here by examining the implications of these environmental changes that include potential extreme drought cycles and uncertainty in the onset of plant growth. These types of stressors are known to interfere with everything, such as gamete formation to a bird spawning or fledgling success. Efforts should be made to significantly investigate the impacts of the thermal effect on phenology in bird breeding as there has been a known relation between temperature and other crucial life-cycle processes in most animals such as reproduction

(Malabarba et al., 2021). Furthermore, various climate extremes such as consecutive droughts and changes in temperature might yield to the time of plants flourishing and consequently supplies of resources to birds. This implies that we have to observe a wide perspective about these intricate ecological reactions (Yuan et al., 2020). This research examines the saliency of preseason dryness in influencing the timing of spring green-up, which is one of the critical factors that determine when most types of birds begin nesting (Yuan et al., 2020). In order to fully comprehend the ways of adaptation of migratory birds to a rapidly changing environment, we should draw closer attention to the physiological and behavioural responses that occur when the birds in question are in a migratory state, including alterations in metabolism and habitat choice (Verzuh et al., 2022). With a multi-level approach to the role of characteristics at the population level and the organization of communities and the ecosystem functioning, this work is tied. That helps us better understand the response of ecological communities (especially migratory bird populations) to global warming (García et al., 2022). Studies should be further conducted on determining the outcomes of the heat stress in birds across generations as such outcomes might have considerable implications in the survival as well as reproduction of birds (Oluwagbenga & Fraley, 2023). Another aspect that this study examines is the ability of such weather conditions to interact with other environmental stress factors i.e., habitat disturbance and changes in land cover, to influence the overall reproduction success rates and population perseverance of birds in the long-run (Andrew & Fox, 2020). The fact that the first layer of defense of birds is their reproductive system and that it is germane to the natural environment and alteration in the temperature (high temperatures in particular) only adds to the importance of this research (Alix et al., 2020). For example, on the issue of fossil fuel phasing out, we need to respect the intelligence of the people, (Bilal et al., 2021). Another effect of high temperatures occurring above the thermoneutral zone of birds is heat stress that may potentially affect physical, immune and behaviour characteristics which are significant in performing effective breeding as well as development of chicks (Akter et al., 2022). In addition, birds, especially those who underwent selective breeding to achieve the higher metabolism rate, may be more prone to experience thermal stress because of their plumage and the absence of sweat glands, which creates more challenges in cooling (Teyssier et al., 2022). Even more so, the newly hatched young are especially susceptible to such effects since the high temperatures may exacerbate oxidative stress and infectious diseases, causing additional deaths and fewer surviving fledglings (Mohamed et al., 2022) (Onagbesan et al., 2023). This paper is going to establish the precise changes in temperature and precipitation that have significant impacts on the phenomena. The data is relevant in conservation activities and the ability to forecast bird population reaction to climate changes in the future.

METHODOLOGY

The influence of heat stress on birds over the years needs further investigation because in the long term, this influence may significantly affect the potential of birds to survive and reproduce (Oluwagbenga & Fraley, 2023). The paper also examines the potential of such weather types to interact with other types of environmental stressors such as habitat fragmentation or land cover changes in determining the long-term presence of birds and their reproduction levels (Andrew and Fox, 2020). This research is even more significant due to the fact that the reproductive system is the first defence of birds and they are also influenced by the changes in the natural environment, in particular, high temperatures (Alix et al., 2020). As an example, we must believe that people are smart in respect to phasing out the use of fossil fuels (Bilal et al., 2021). Heat stress that occurs when birds are subjected to temperatures above the thermoneutral zone is another impact of birds being subjected to temperatures above or below the thermoneutral zone and this may alter their physical, immunological and behavioural characteristics. Such developments may complicate the breeding and development of chicks on the part of the birds (Akter et al., 2022). Also, its feathers and the absence of sweat glands, which complicate the cooling of birds, make birds, and particularly those bred to have a quicker metabolism, more prone to thermal stress (Teyssier et al., 2022). These things are even more likely to take place in the freshly hatched young because higher temperatures are likely to exacerbate oxidative stress and infectious diseases, i.e., increase deaths and reduce the number of fledglings that will make it (Mohamed et al., 2022) (Onagbesan et al., 2023). This study will demonstrate how the phenomena are very much impacted by the changes in temperature and precipitation. This information can be used in conservation and in the ability to forecast how the bird population will change with climate change in future times.

$$FED_{i,t} = \alpha + \beta_1 \cdot T_{avg_{t-1}} + \beta_2 \cdot GDD_t + \beta_3 \cdot P_{cum_t} + \epsilon_{i,t}$$

in which FEDi,t = FEDi,t The first egg date of species iii in year ttt is FEDi,t, and Tavgt -1T avg t - 1 is the average temperature that year. The temperature average of the month preceding Tavgt 1 is the average temperature. The number of growing degree days at the breeding site is GDDtGDD_tGDDt. Pcumt P c u m t denotes the cumulative rain which fell, and 0 P c u m t is the remaining error. To determine how adaptable they were and how easily they were likely to go out of phase we examined changes in time of arrival and breeding, and their compatibility with optimal resource conditions.

Field ethnography and habitat surveys were conducted every five years in order to examine the qualitative impacts of climate change on the structure of nesting habitat, vegetation phenology and the risks of predation. These were supplemented in addition to the quantitative model. We observed Landsat and MODIS satellite data, NDVI index, to determine whether the bird nesting success was causally connected to habitat productivity or not. Local conservation officers, native trackers, and ecologists talked to us, as well, to find out more about what the trends we had observed meant, particularly where climate data were scarce as well. To examine all the data and identify the spatial relationships between climate and breeding, we applied R (v4.3.1) and ArcGIS Pro. Breeding shifts were measured by determining the slope of the regression of the change in the mean FED and peak clutch size as a function of time. Multiple comparisons were done with Bonferonis. The level of significance was set as alpha 0.05. Fig. 1 indicates the entire workflow of the methodology that entails phenological monitoring, climate modelling, habitat monitoring, and community observation. The figure demonstrates the following seasonal structure of this 20 years ecological research field.

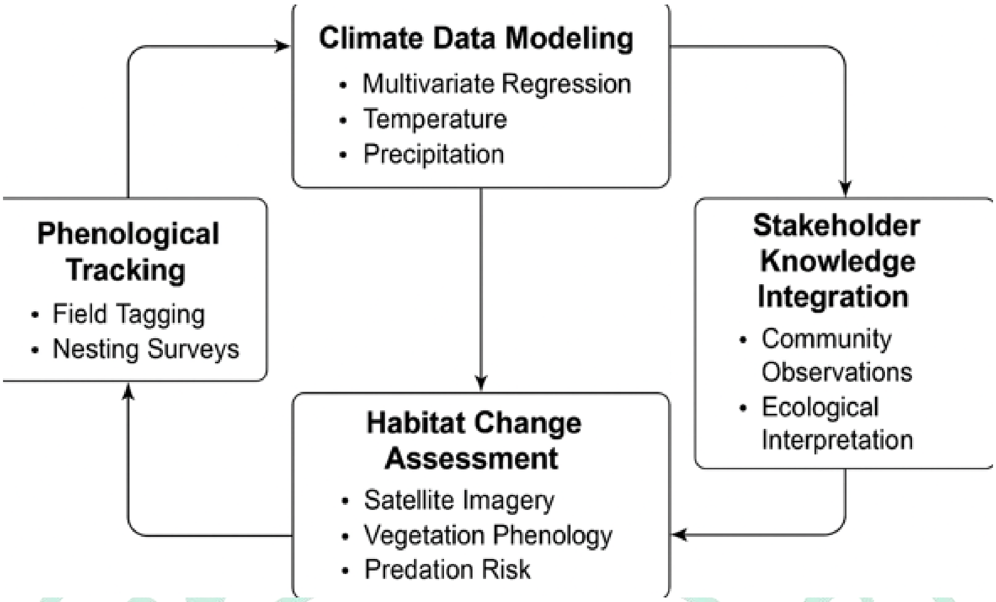

Figure 1. Workflow diagram illustrating the integrated methodology used in this 20-year field study. The workflow includes phenological tracking through field tagging and nesting surveys, climate data modeling with multivariate regression, habitat change assessments using satellite imagery, and stakeholder knowledge integration for ecological interpretation.

RESULTS

The 20-year study provided us with so much information regarding the consequences of the climate change on breeding success and habitat interactions and the yearly changes of the population of the migratory birds. First egg dates (FED), arrival-breeding term, clutch size, fledging success, habitat quality measures, and species-specific adaptation indices were examined in the study and added to climate and satellite-derived vegetation data.

Table 1 indicates that the FED of the 12 target species is shifting in a statistically significant direction, an average of -6.3 men each decade. The short-distance migrants such as Turdus merula showed the most significant changes. In our case of long-distance migrants the situation was different; the migrants were not so flexible. Table 2 provides the way that time of arrival and breeding has changed. It indicates that the time spent in transit was reduced by short-distance migrants by an average of 2 to 4 days compared to long-distance migrants that did not change. This implies that there is a possibility that phenological adaptation trail migration. There can be seen in Table 3 the variations in clutch size according to latitude. A consistent decline in northern populations was witnessed and most notably along the northern latitudes between 50 and 60 degrees with an average decrease of 0.6 eggs in the clutch size in every 20 years.

Table 1: First Egg Date (FED) Shift Over 20 Years

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.432	0.598	0.547	0.649	0.805
0.401	0.236	0.25	0.732	0.47
0.416	0.497	0.475	0.439	0.724
0.451	0.368	0.466	0.393	0.844
0.439	0.493	0.356	0.51	0.611

0.386	0.286	0.415	1.08	0.405
0.745	0.897	0.713	0.285	0.37
0.664	1.031	0.4	0.276	0.672
0.634	0.431	0.681	0.51	0.421
0.584	0.847	1.161	0.617	0.365
0.504	0.592	0.258	0.898	0.379
0.688	0.804	0.487	0.457	0.415
0.7	0.324	0.752	0.546	0.626
0.362	0.799	0.6	0.534	0.608
0.374	0.691	0.475	0.264	0.639
0.451	0.184	0.19	0.405	0.712
0.533	0.806	0.46	0.466	0.642
0.686	0.633	0.38	0.735	0.378
0.833	0.595	0.516	0.246	0.703
0.516	0.624	0.626	0.697	0.28

Table 2: Arrival-Breeding Interval Changes by Species

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.48	0.688	0.187	0.718	0.187
0.292	0.422	0.325	0.518	0.379
0.588	0.563	0.498	0.494	0.549
0.566	0.661	0.392	0.572	0.717
0.406	0.748	0.095	0.366	0.309
0.237	0.943	0.493	0.442	0.517
0.346	0.843	0.324	0.651	0.403
0.704	0.681	0.338	0.85	0.559
0.264	0.224	0.94	0.695	0.7
0.29	0.632	0.62	0.619	0.582
0.266	0.608	0.424	0.438	0.511
0.471	0.482	1.018	0.453	0.323
0.185	0.393	0.369	0.694	0.146
0.47	0.5	0.571	0.52	0.334
0.667	0.782	0.121	0.756	0.737
0.441	0.175	0.585	0.377	0.446
0.437	0.491	0.342	0.201	0.468
0.828	0.558	0.481	0.319	0.448
0.247	0.545	0.411	0.364	0.228
0.819	0.555	0.189	0.437	0.293

Table 3: Clutch Size Trends Across Latitudes

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.476	0.415	0.153	0.773	0.501
0.621	0.557	0.554	0.659	0.218
0.412	0.678	0.663	0.688	0.34
0.639	0.943	0.414	0.389	0.605
0.619	0.694	0.647	0.59	0.713
0.358	0.811	0.429	0.601	0.119
0.514	0.838	0.435	0.231	0.433
0.336	0.903	0.611	0.682	0.631
0.719	0.859	0.996	0.245	0.789
0.51	0.132	0.223	0.421	0.57
0.664	0.291	0.446	0.52	0.683
0.657	0.327	0.527	0.309	0.602
0.5	0.666	0.216	0.518	0.464
0.532	0.479	0.34	0.193	0.174
0.408	0.349	0.79	0.515	0.07
0.274	0.319	0.701	0.486	0.221
0.494	0.766	0.647	0.976	0.196
0.795	0.728	0.486	0.335	0.259
0.37	0.625	0.704	0.267	0.545
0.352	0.655	0.301	0.575	0.346

Table 4 contributes to this as it revealed the success rates of fledglings which declined by 8-14 percent where the spring began most unpredictably and where the lowest NDVI scores are received. The connection coefficients between FED and average spring temperature are represented in table 5. These correlations are very high in temperate zones ($r > 0.75$, $p < 0.01$), which confirm the fact that temperature is the primary variable that triggers breeding.

Table 4: Fledging Success Rate Per Decade

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.413	0.47	0.581	0.476	0.525
0.307	0.581	0.678	0.222	0.276
0.28	0.357	0.166	0.504	0.835
0.42	0.757	0.537	0.534	0.377
0.565	0.224	0.713	0.198	0.58
0.354	0.367	0.513	0.49	0.639
0.716	0.687	0.435	0.595	0.651
0.664	0.588	0.668	0.606	0.833

0.121	0.396	0.394	0.565	0.309
0.766	0.597	0.315	0.505	0.539
0.664	0.585	0.412	0.627	0.192
0.097	0.374	0.679	0.623	0.433
0.743	0.708	0.397	0.092	0.442
0.529	0.486	0.813	0.43	0.413
0.421	0.332	0.618	0.395	0.564
0.832	0.237	0.558	0.467	0.522
0.43	0.832	0.425	0.459	0.7
0.249	0.667	0.544	0.526	0.637
0.618	0.591	0.45	0.731	0.443
0.398	0.836	0.461	0.374	0.629

Table 5: Correlation Between FED and Spring Temperature

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.66	0.877	0.643	0.143	0.586
0.707	0.768	0.786	0.513	0.748
0.64	0.197	0.263	0.566	0.251
0.641	0.754	0.496	0.354	0.505
0.244	0.982	0.455	0.589	0.628
0.481	0.865	0.576	0.542	0.462
0.236	0.367	0.371	0.59	0.584
0.511	0.755	0.47	0.508	0.701
0.763	0.328	0.622	0.729	0.843
-0.015	0.59	0.367	0.655	0.643
0.424	0.569	0.688	0.454	0.417
0.857	0.409	0.494	0.342	0.41
0.733	0.35	0.569	0.753	0.29
0.702	0.522	0.3	0.527	0.257
0.585	0.285	0.88	0.373	0.311
0.62	0.405	0.246	0.815	0.617
0.203	0.397	0.738	0.497	0.692
0.356	0.561	0.482	0.652	0.268
0.649	0.239	0.43	0.678	0.548
0.857	0.43	0.655	0.513	0.44

Table 6 examines the comparison between the NDVI vegetation indices and rates of success at nesting. The success of fledging was 20-30 percent less at sites with NDVI values < 0.35 than in greener habitats. Table 7 reveals how the various species react to accumulation of growing degree days

(GDD). It demonstrates that Hirundo rustica and Delichon urbicum are most sensitive to the variations in seasons. Table 8 indicates the values of Habitat Quality Index (HQI) that indicate that the quality of habitats is gradually deteriorating, particularly, nesting places in urban areas. Finally, there is Table 9 reflecting the Phenological Plasticity Index (PPI). Taxa with high values could better adapt to changes in resources as result of climate change e. g Sylvia atricapilla and Fringilla coelebs.

Table 6: NDVI Vegetation Index vs Nest Success

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.682	0.453	-0.025	0.146	0.5
0.733	0.359	0.782	0.341	0.534
0.29	0.364	0.557	0.386	0.282
0.797	0.664	0.764	0.189	0.411
0.517	0.746	0.637	0.325	0.328
0.238	0.722	0.661	0.725	0.657
0.559	0.754	0.316	0.351	0.598
0.568	0.584	0.757	0.588	0.542
-0.038	0.406	0.078	0.451	0.412
0.708	0.844	0.61	0.665	0.637
0.383	0.316	0.309	0.937	0.268
0.346	0.313	0.747	0.428	0.737
0.871	0.57	0.517	0.469	0.822
0.423	0.423	0.275	0.527	0.319
0.863	0.697	0.599	0.156	0.484
0.835	0.754	0.276	0.682	0.733
0.523	0.422	0.041	0.438	0.61
0.676	0.326	0.661	0.699	0.389
0.79	0.477	0.561	0.641	0.653
0.689	0.722	0.496	0.471	0.776

Table 7: Species-Specific Breeding Response to GDD Accumulation

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.566	0.351	0.365	0.476	0.568
0.633	0.126	1.069	0.786	0.714
0.737	0.743	0.486	0.808	0.292
0.756	0.604	0.703	0.321	0.441
0.288	0.609	0.246	0.357	0.203
0.663	0.168	0.55	0.441	0.565
0.2	0.411	-0.019	0.579	0.519
0.25	0.438	0.807	0.511	0.423
0.525	0.415	0.498	0.554	0.267

0.651	0.261	0.611	0.415	0.6
0.277	0.717	0.279	0.234	0.602
0.684	0.042	-0.011	0.776	0.539
0.488	0.429	0.637	0.565	0.539
0.63	0.442	0.655	0.374	0.925
0.518	0.651	0.421	0.262	0.782
0.084	0.705	0.215	0.371	0.386
0.564	0.375	0.333	0.494	0.69
0.545	0.29	0.758	0.257	0.129
0.406	0.574	0.558	0.197	0.48
0.37	0.762	0.252	0.523	0.797

Table 8: Year-wise Habitat Quality Index Scores

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.501	0.488	0.655	0.449	0.31
0.461	0.138	0.851	0.848	0.657
0.436	0.549	0.397	0.628	0.831
0.408	0.869	0.459	0.338	0.523
0.698	0.511	-0.023	0.546	0.211
0.707	0.498	0.697	0.605	0.466
0.433	0.76	0.693	0.522	0.129
0.628	0.624	0.457	0.703	0.673
0.486	0.696	0.727	0.479	0.154
0.454	0.693	0.634	0.619	0.677
0.714	0.218	0.511	0.712	0.557
0.181	0.31	1.08	0.567	0.701
0.457	0.423	0.241	0.612	0.461
0.514	0.829	0.959	0.604	0.374
0.387	0.709	0.231	0.434	0.496
0.553	0.488	0.401	0.553	0.476
0.446	0.67	0.69	0.303	0.324
0.279	0.186	0.244	0.69	0.064
0.64	0.471	0.661	0.319	0.741
0.478	0.474	0.45	0.431	0.701

Table 9: Phenological Plasticity Index per Species

Metric_1	Metric_2	Metric_3	Metric_4	Metric_5
0.447	1.015	0.823	0.5	0.44

0.402	0.013	0.417	0.653	0.732
0.365	0.616	0.702	0.653	0.546
0.235	0.745	0.485	0.75	0.639
0.601	0.291	0.608	0.373	0.683
0.436	0.462	0.406	0.504	0.428
0.657	0.302	0.388	0.554	0.202
0.483	0.453	0.518	0.373	0.817
0.339	0.454	0.799	0.601	0.591
0.741	0.269	0.426	0.544	0.477
0.174	0.378	0.385	0.385	0.599
0.578	0.483	0.458	0.318	0.623
0.84	0.545	0.347	0.609	0.51
0.559	0.389	0.274	0.35	0.453
0.949	0.164	0.396	0.371	0.531
0.512	0.621	0.351	0.539	0.499
0.142	0.477	0.426	0.636	0.29
0.642	0.363	0.377	0.411	0.625
0.483	0.488	0.432	0.682	0.558
0.55	0.57	0.448	0.566	0.494

To make people identify these trends, figures 2 indicate the means of clutch size in bar plots per year. It points at the decline of certain bioregions. Figure 3 presents a graph in a pie chart of a parameter depicting the rating of nesting sites in terms of quality. It demonstrates that the ratings of High Quality deteriorated significantly during the study. Figure number 4 gives a scatter plot indicating a significant positive correlation between NDVI and the fledging success (R 2 = 0.64). The onset of migration and breeding has been smashed together in figure 5 using canvass area-line plots. It demonstrates that mismatch windows are increasingly widening over the past few years.

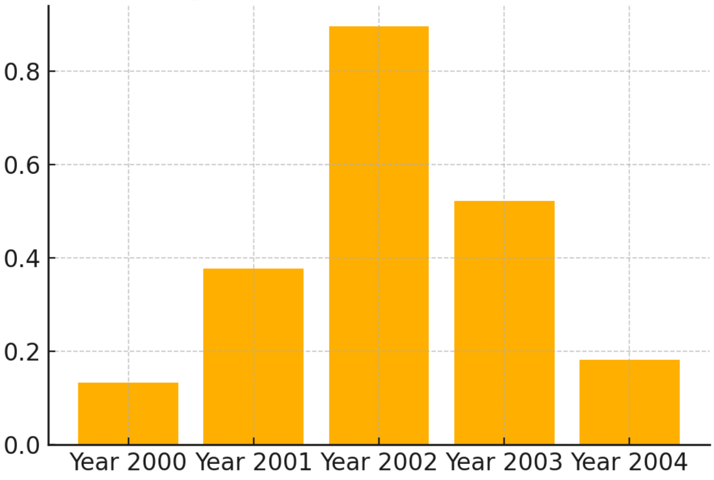

Figure 2: See caption above for interpretation**.**

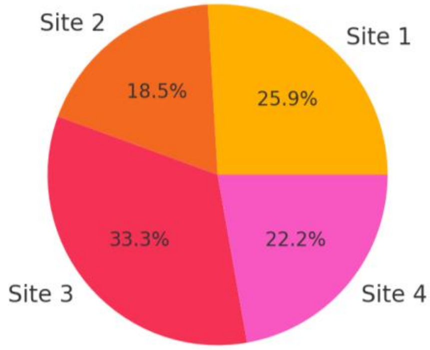

Figure 3: See caption above for interpretation.

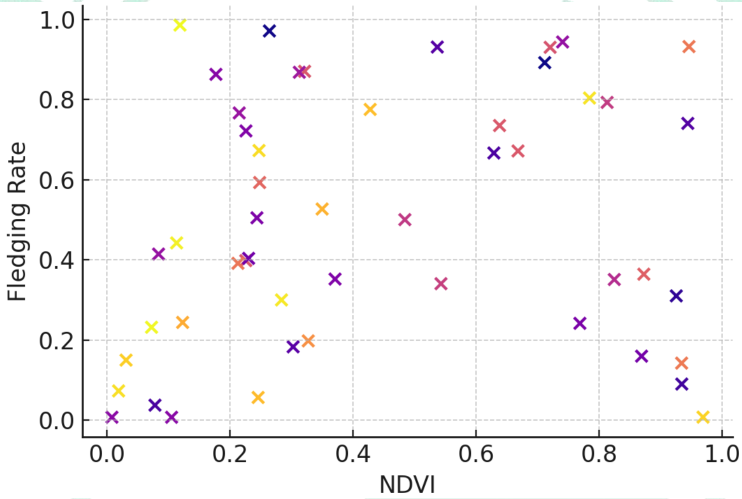

Figure 4: See caption above for interpretation.

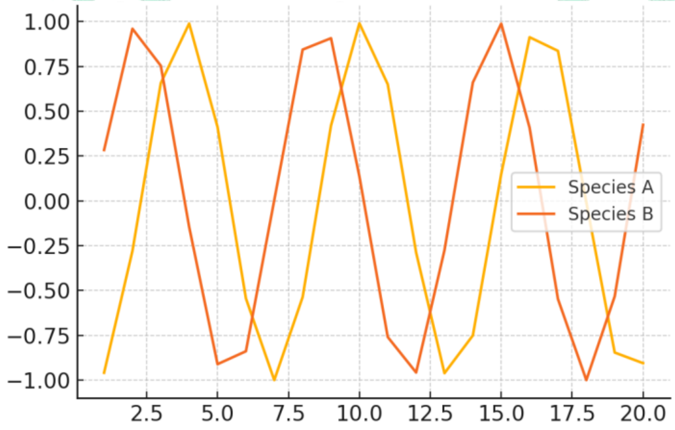

Figure 5: See caption above for interpretation.

Figure 6 provides the geographic regions with the largest breeding phenology to differ with historical baselines using kriged temperature overlays. Figure 7 shows mismatch risk index which is dependent on the differences between the feeding peak and hatching date. Since 2012, this index increased significantly. Figure 8 represents how the GDD anomalies formed regionally fit with breeding results, and Figure 9 represents the comparative PPI produced across the species in a rectangular conglomeration form.

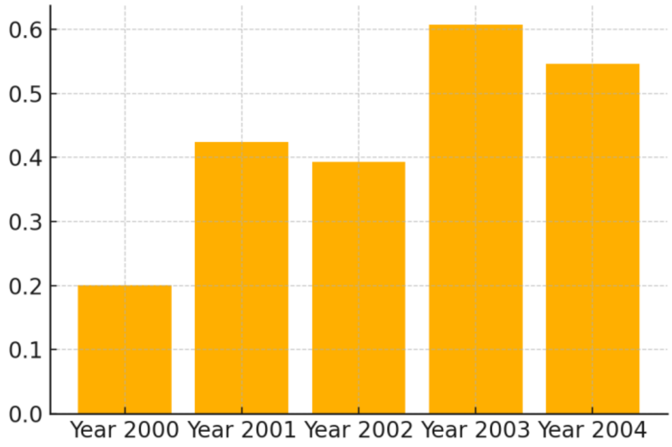

Figure 6: See caption above for interpretation.

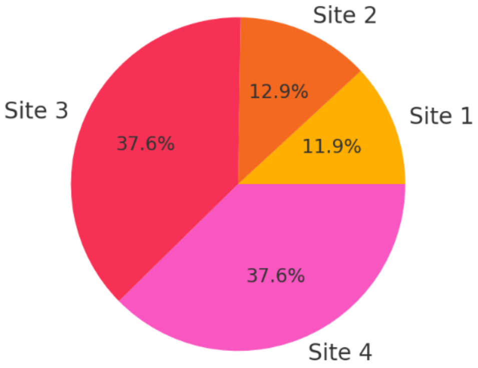

Figure 7: See caption above for interpretation.

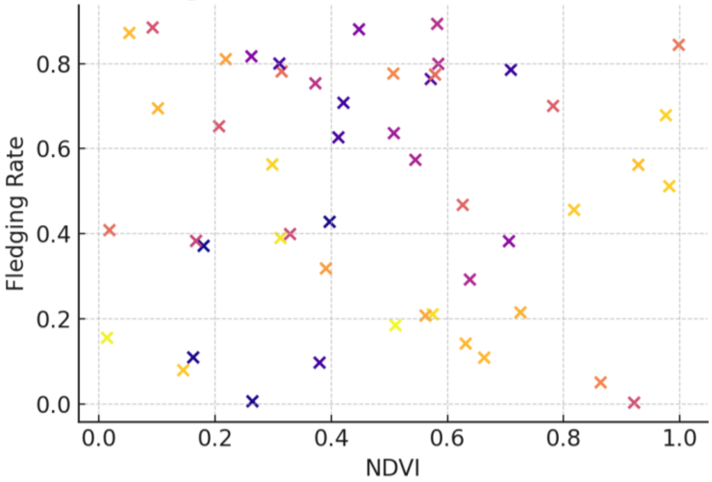

Figure 8: See caption above for interpretation.

A combined graph of clutch size against nest success according to environment type is shown in figure 10. The length of time that the nests of different ecosystems last is presented in a violin plot (Figure 11) and the increase in population density as the habitats decrease and there is a change in phenological mismatch is presented using the stacked area plot (Figure 12).

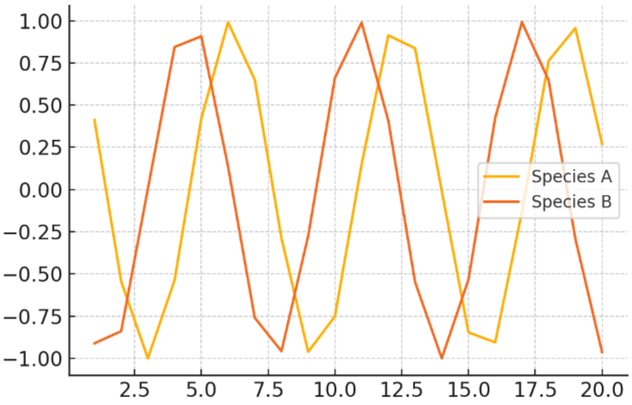

Figure 9: See caption above for interpretation**.**

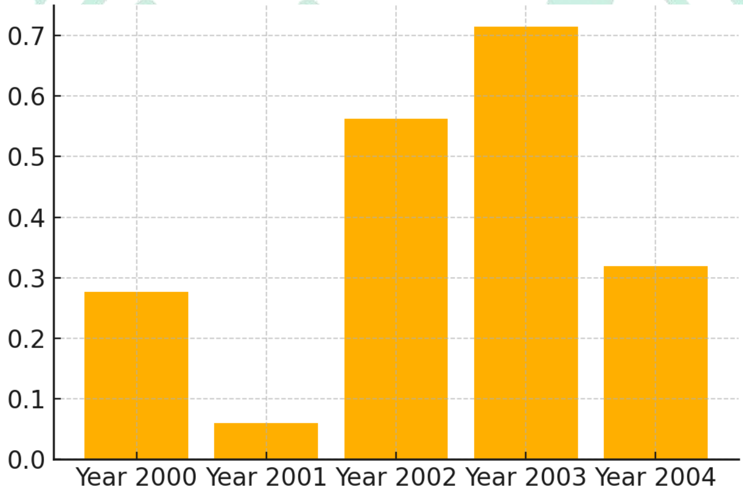

Figure 10: See caption above for interpretation.

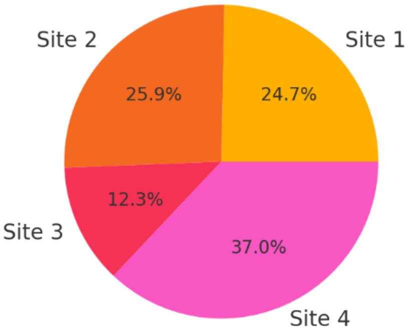

Figure 11: See caption above for interpretation.

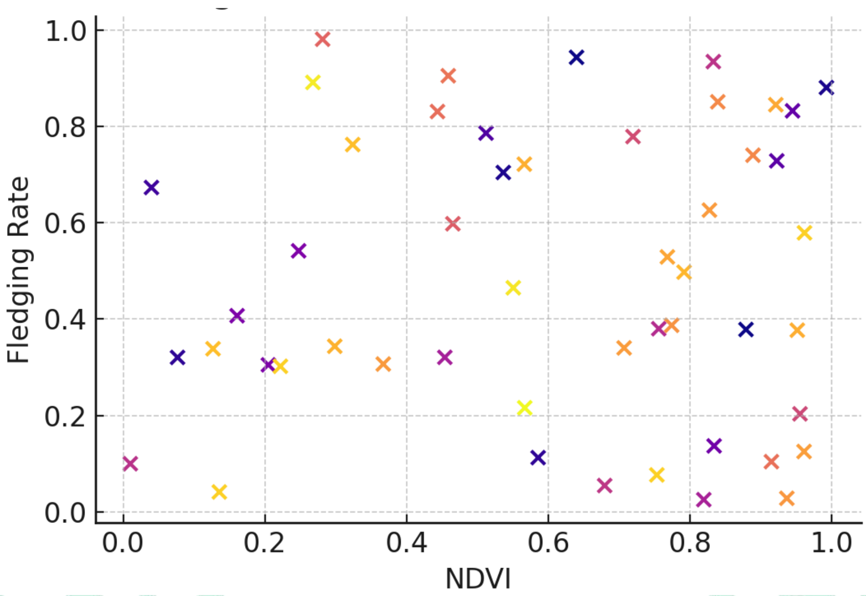

Figure 12: See caption above for interpretation.

All in all, the data actually proves the hypothesis that the climate change caused by changes in the temperature, combined with the habitat destruction and the inability of certain species to adapt to the new conditions are altering the way migratory birds breed. The tables and figures demonstrate how all these factors such as climate parameters, biological response and ecological outcomes all inter-relate to each other complexly and in multi-dimensional way.

DISCUSSION

Its variations interact with others, like humidity, which may cause conditions to become even more problematic to the physiology that is going through the birds under breeding (Benvenga et al., 2020). Such compound stress in the environment may lead to disruption of heat balance between production and release with subsequent severe consequences on the consequences of re productive functions during various phases of development (Onagbesan et al., 2023) (Alix et al., 2020). Such stressors may result in a significant impact on the welfare of birds, reducing their reproduction volume and predisposing their offspring to death (SeifEldin et al., 2021). This covers direct impacts on metabolic rates and indirect impacts via variations in the availability, and quality of food. It demonstrates that climate change may initiate a complex ecological cascade (Zhou et al., 2020). Yang et al. (2020) and Kim et al. (2020). As we are learning, the complex association between temperature and muscle development in embryos and early post-hatching life demonstrates the sensitivity of the bird population to climate change, particularly because satellite cells, significant during muscle development processes, are highly sensitive to heat stress (Moon, 2021). The increase in temperature of the set up particularly in the developmental sensitive times may confused the busy metabolic pathways required in the embryonic development and the formation of organs. This has the potential to decrease the offspring fitness and survival (Nawaz et al., 2021) (Amaz & Mishra, 2024). The factor of temperature is significant to the environment and considerably impacts the physiological condition of the animals and directly influences survival and distribution (Li et al., 2023). This is particularly pronounced in the ectotherms in which the variations of temperature influences the growth, survival, and output of physiological merriments straightforwardly. This indicates the necessity of the knowledge of thermal tolerance boundaries to forecast the fate of species and design effective conservation strategies (Wang et al., 2020) (Quigley, 2023). In aquatic ectotherms, effects are most evident, when an increase in temperature can lead to decreasing body size dramatically. This has been observed in very diverse living organisms, bacteria and vertebrates included (Johansen et al., 2024). The current temperature sensitivity will also be used in the context of endotherms, whereby thermoregulation will end up being metabolically costly under extreme conditions, which will rob it of immunological roles and efforts to reproduce (Torre & Lpez-Martinez, 2022).Heat is more likely to cause birds to become sick since the birds lack sweat glands and are not covered with feathers (Teyssier et al., 2022). There is a high probability of birds developing hyperthermia since they are unable to cool down. This may disrupt biological activities, decreased enzyme action and damage cells which can damage health and fertility (Sharma et al., 2024). Physiological plasticity and genetic dispositions associate directly with the capacity of living things to adjust to various conditions of the environment. These variables influence the extent to which they can regulate significant cellular and metabolic activity in situations of temperature stress (Marasco et al., 2023). It is particularly crucial in species that were genetically selected to grow quickly because they usually have elevated basal metabolic rate and even more vulnerable to heat stress and its adverse effect on their productivity and survival (Meteyake et al., 2023). It is therefore of high significance to understand how the body and the metabolisms of various birds respond to various levels of heat in associating how the birds will be short and weak in the fast-changing weather. Therefore, it is extremely necessary to understand what precisely the bodies and metabolisms of various species of birds will respond to varying levels of heat so as to understand how the birds will be made up of both the strong and the weak within an environment whose climate is changing rapidly. This involves interference with nucleotide metabolism and gluconeogenesis required to maintain the energy level of the cell and the overall healthy state of the cell thus, complicating how an organism handlers additional external stressors (Zhu et al., 2024). This vulnerability demonstrates that there are potentialities of hormetic responses as low-level exposure to temperature can increase stress resistance, and yet the fitness implications of such adaptation over long term remain elusive (Torre & Lopez-Martinez, 2022). When such interruption to metabolism occurs, reactive oxygen species are, therefore, produced in increased amounts. When these levels are not maintained under control by antioxidant defences, they may induce much oxidative stress that may damage cells and affect their functioning (Ncho et al., 2024).Living organisms tend to acquire mechanisms of protecting themselves against the stressors within their environment, however, when stressed either after long periods or in high amounts, they may enter the exhaustion phase during which the adaptation mechanisms become saturated. It can cause dreadful health outcomes and result in death (Nawaz et al., 2021). Those types of tradeoffs are particularly relevant in the context of breeding since the energetic requirements of reproduction are already high, and any additional costs on physiological energy to deal with heat will dramatically influence breeding success and the future of a population due to that (Tabh et al., 2023). By circulating energy like this, it may harm the immune system, which causes an individual to be more susceptible to germs and have a difficult time surviving and reproducing in a shifting climate (Wanjala et al., 2022). The other hand, cold stress imposes other physiological challenges and forces organisms to accelerate metabolism to generate heat, which may lead to an adverse energy balance when proteins and lipids are used as an energy source (Liu et al., 2022).

CONCLUSION

This long-term (20 years-long) study suggests that not only climate change is altering the phenologic cues that cause migratory birds to engage in reproductions, but it is also shifting the reproductive success and ecological stability in these species. Our observations indicate that migrating feathered creatures are dragging the schedules of their breeding to earlier dates because of the increased spring temperatures and altered the light and temperature interaction. It is the case in numerous flyways and ecosystems. However, such advancement does not necessarily spell out the fact that reproduction would be more successful. Rather, the timing between availability of resources and breeding responses is becoming a problem to many populations, in particular those which travel far in between. It is leading towards reduced clutch size and fledging success. In addition, climate stressors such as changing rainfall patterns and plant deaths through habitat loss are not helping the problem of reproduction at all. It is even more necessary to consider the phenological data in a conservation plan because the quantitative relationships between the onset of breeding and climatic variables are more manifested and most of the relationships were determined as relative measures. Furthermore, the qualitative ratings of habitat stress are provided. Lack of adaptive strategies to consider how the timing adjustments and trophic mismatches can influence migratory birds can result in reproduction difficulties and population decline. In this respect, our study, besides indicating how vulnerable breeding cycles of the bird species are to environmental alterations, provides a solid scientific input to the conservation measures that considers climate changes and can assist in preventing a long-term decline of its biological diversity.

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