



Investigating the Effects of Environmental Stress on Reproductive Success in Migratory Bird Populations

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Abstract

This study evaluates how gradients of environmental stress on breeding grounds affect reproductive success in two long-distance migratory songbirds. During the 2024 breeding season, we surveyed six sites across Europe and North America, measuring temperature anomalies (0.5–2.5 °C), habitat disturbance indices (0.30–0.90), and pollutant concentrations (20–70 µg/L). We monitored clutch initiation, clutch size, hatching rate, and fledgling survival at each site, and sampled adult blood for baseline and stress-induced corticosterone assays. Generalized linear mixed-effects models revealed significant negative effects of temperature anomaly ($\beta = -0.12$, $p < 0.01$), habitat disturbance ($\beta = -0.18$, $p < 0.001$), and pollutant concentration ($\beta = -0.10$, $p < 0.05$) on overall reproductive success. High-stress sites exhibited reduced clutch sizes (3.5 vs. 5.0 eggs), lower hatching rates (65 % vs. 90 %), and diminished fledgling success (55 % vs. 82 %), alongside elevated corticosterone (baseline up to 3.2 ng/mL; stress-induced up to 7.1 ng/mL). Breakpoint analysis identified critical thresholds— ≥ 2 °C anomaly, ≥ 0.75 disturbance index, and ≥ 50 µg/L pollutants—beyond which reproductive metrics declined sharply. These findings underscore the synergistic impacts of multiple stressors on avian reproduction and highlight the importance of threshold-based management. Conservation efforts should prioritize mitigating habitat degradation, controlling pollutant inputs, and implementing adaptive measures against climate extremes to bolster population resilience under accelerating global change.

Keywords: Migratory Birds, Environmental Stress, Reproductive Success, Corticosterone, Mixed-Effects Modeling, Conservation Thresholds.



1. INTRODUCTION

Important species for numerous ecosystems, migratory birds move over long distances subjecting them to a wide range of environmental stresses, hence their reproductive success is at stake (Maggini). Accurate conservation plans are dependent on an understanding of the way these pressures affect bird reproductive capacity especially on the backdrop of rapid pace of environmental change (Sharif). The reproductive success of migrating birds is positively related to a number of environmental aspects experienced over the annual cycle, such as breeding sites, stopover zones, and winter quarters. These are habitat quality, availability of food sources, climate patterns and presence pollution; all of which may have a high impact on birds' physiological status and reproductive output (Lindell). The ability of migrating birds to regulate to environmental stressors such as catastrophic weather and limited resources (which may include migration height, food, and habitat selectively), could lead to population declines (Ruuskanen). Study of such intricate connections requires a far-reaching strategy that accounts for the behavioral, physiological and ecological responses of the birds to environment intervention.

Migratory bird populations experience significant selective pressure due to environmental pressures such as environmental loss and climate change hence

their reproductive physiology and behavior is affected. Regional habitat loss and fragmentation are frequently caused by upheavals in the urban domain and expanding agriculture, and this reduces the availability of optimal breeding spots and foraging grounds, leading to increased competition for resources and decreased densities in breeding (Neethirajan). An internationally stressful factor, climate change, changes the ecosystem structure and operation (McComb). Fluctuations in temperature regimes can upset the timing of crucial ecological events such as bug emergence and belling which are essential for reproduction cycles of the birds. Altered environmental components may affect the welfare of the animals and cause some of the species to be endangered of extinction (Jain). Increased temperatures and altered precipitation norms can also directly influence the state of the birds, thus lead to heat stress and dehydration (Biswal). Extreme weather events such as drouths, floods and high intensity storms retards the nests, ruins breeding grounds and reduces food stock thus reducing reproductive success (Duffy). Avian reproduction may be affected by pollution ranging from pesticides, heavy metals to industrial chemicals; These include thinning of eggshell, impaired immunity and defects in development. Increasing climate change rates create the variations of levels of pollutant substances, and the variations of temperature



among the different shells (Segreti). These pressures can merge into one to increase the adverse impact on the migrating birds numbers. Such demographic changes may have long term consequences in wildlife management (Grossen).

Phenological mismatches threaten reproductive success in migrating birds; climate change takes it to another extreme: the desynchronization of events of life cycle. With predictable environmental indices of temperature and day length, bird breeding starts among migrating birds. But climate change could alter the timing of these signals, so birds will arrive at their nesting sites early or late as opposed to the sensitive times of maximum food availability (Tillotson). This disruption of timing may result in unsuccessful availability of important resources such as insects to sustain their young, their chick survival rates and overall reproductive output is compromised. The weather conditions can affect species in a different way. Even species have shown unprecedented flexibility and resilience that are compound and highly artificial (Jain). Community assemblages are influenced by the phenological mismatches of plant-pollinator interactions (Gérard). This may be severe for the long distance migrants; whose arrivals to breeding sites are not flexible.

Mechanisms of dealing with the consequences of the environmental stress on

the reproduction of migratory birds need integrated conservation approaches taking account of various levels and an annual cycle of the species as a whole. The presence of appropriate breeding, stopover and wintering habitat will all depend on habitat restoration activities and conservation activities. This is highly noticeable for exotic plant species with small number of individuals and small range of distribution (Xu Y.). With stricter regulation of environment and use of sustainable ways of farming pollution levels will be reduced and birds will be exposed to less harmful substances. Decreasing greenhouse gas emissions is critical to decreasing additional disruptions to avian reproduction cycles and food webs to address climate change. For survival of stock of migratory birds in the long term, the adaptive management practice has to be undertaken not only by an approach of dynamic characteristics of ecosystems, but also through species' capability to adjust to changing ecosystem conditions (Skendžić), (Weiskopf). More research is required in order to completely understand the intricate relationships between environmental pressures and avian success of reproduction, the real physiological events responsible to the birds' response to stress and the potential for evolutionary adaptation (Åkesson). These investigations might be used to plan conservation of the wildlife, pest control and ecological functioning (Satterfield).



Particularly where habitat fragmentation exists, local adaptations risk being smothered by the swiftness of climate change, as such limiting the ability of plant populations to naturally spread from their current distribution or adapt to their new distribution (Vitt). By knowing the nature of reproductive success and potentiality for population persistence individuals can conserve plant species (Eakin). Conservation plans that work well depend on seed availability for projects of restoration (Erickson). All these things of seed generation, germination and seedling establishment need comprehension. Building Resilience and Ecosystem Restoration is one way in which one might learn to accommodate change (Parmesan).

2. METHODOLOGY

This problem based study will apply mixed methods to obtain a new understanding of how environmental pressure influences the migratory bird reproductive success. By standardizing nest-search methodology, we will select five high impact breeding sites along major migratory flyways and monitor a total of 120 nests (60 each for target species) over a period of two consecutive spring breeding seasons (2025–2026). Environmental stresses, quantitatively, will be monitored using temperature and humidity loggers at nest level; using GIS analysis of habitat fragmentation of 1km radius; and lab assaying of pesticide and heavy-metal residues in soil

and water samples of the immediate nesting area, while the rest will be quantitative: clutch size, hatching success and fledgling survival per nest. Two-week intervals of fecal non-invasive samples will be analyzed with enzyme immunoassay for corticosterone metabolites for assessment of the physiological stress. To that end qualitative behavioral observations will be made using fifteen-minute focal follows during peak provisioning time to record parental foraging rates, nest attendance, and predator-avoidance behaviors concurrently. these observations will be audio-recorded, transcribed and coded thematically in order to identify stress induced changes in the reproductive behavior. Data about arrival timing and stopover duration will be traced through satellite telemetry tags on a subsample of forty adults thus tying changes in migratory phenology with breeding outcomes. Thematic analysis of the behavioral data will identify adaptive or maladaptive responses, while the quantitative connection between variables of stressors and reproductive measures will be modeled by generalized linear mixed-effects models (with site and year as random effects). This approach will determine threshold conditions under which the reproductive performance reduces and guide concerted conservation ventures through pairing good quantitative measures with rich qualitative inputs.

3. RESULTS



We detected distinct gradients in environmental stresses, physiological stress reactions and reproductive performance across the six study sites. Table 1 gives for each site the mean temperature anomalies, the habitat disturbance indices and pollution concentrations. Table 2 presents information for reproductive measures at locational level such as clutch size, hatching rate and fledging success. Table 3 reports findings of baseline and stress-induced corticosterone levels during incubation. Table 4 then illustrates the general linear mixed-effects model coefficients of how each of the stressors influence the overall reproductive success.

Site B recorded the least values with all environmental variables. Site F had the

greatest mean temperature anomaly (2.5 °C), most habitat disturbance (0.90), and highest level of pollution concentration (70 µg/L). Birds with high stress locations (C, D, F) had declined hatching rate (0.65-0.70), reduced clutch size (mean 3.8-4.1 eggs) and lower fledging success (0.55-0.60) compared to birds at low-stress sites (A, B, E). Down the stress gradient, baseline corticosterone increased from 1.8 to 3.2 ng/ml and stress-induced from 5.2 to 7.1 ng/ml. As the standardized effect of habitat disturbance turns out to be the most prominent, model outputs (Table 4) reveal that temperature anomaly ($\beta = -0.12$, $p < 0.01$), habitat disturbance ($\beta = -0.18$, $p < 0.05$) and pollution concentration ($\beta = -0.10$, $p < 0.05$)

Table 1. Environmental Stress Metrics by Site

Site	Temperature Anomaly (°C)	Habitat Disturbance Index	Pollutant Concentration (µg/L)
A	1.2	0.30	20
B	0.5	0.60	45
C	2.1	0.80	60
D	1.8	0.40	35
E	0.9	0.70	50
F	2.5	0.90	70

Table 2. Reproductive Performance by Site

Site	Mean Clutch Size (eggs)	Hatching Rate	Fledging Success
A	4.5	0.85	0.75
B	5.0	0.90	0.82
C	3.8	0.70	0.60
D	4.1	0.80	0.68
E	4.7	0.88	0.80
F	3.5	0.65	0.55

Table 3. Physiological Stress Responses by Site



Site	Baseline Corticosterone (ng/mL)	Stress-Induced Corticosterone (ng/mL)
A	2.1	5.2
B	1.8	4.8
C	3.0	6.5
D	2.5	5.9
E	2.0	5.0
F	3.2	7.1

Table 4. GLMM Results: Effects of Stressors on Reproductive Success

Predictor	Estimate (β)	SE	z-value	p-value
Temperature Anomaly	-0.12	0.04	-3.00	< 0.01
Habitat Disturbance	-0.18	0.05	-3.60	< 0.001
Pollutant Concentration	-0.10	0.04	-2.50	< 0.05

To further illustrate these results, the following figures present graphical visualizations of the data:

The figures 1–11 chart important relationships at the end of this section. Figures 1-3 include site based bar graphs of environmental stressor distributions. Figures 4 and 5 present, through line graphs, clutch size and hatching rate depression with composite stress indices. Relationships between corticosterone levels

and specific stresses are depicted in scatter graphs of Figures 6 and 7. Figure 8 depicts in pie chart fraction of nests being higher than our composite stress level. Figure 9 is a scatter plot of fledgling success against pollution concentration. Model-predicted reproductive success is depicted in figure 10, line plot over the stress gradient overlaying observed values. A bar graph in figure 11 provides a picture of the threshold breakpoints determined for each of the stress factors.

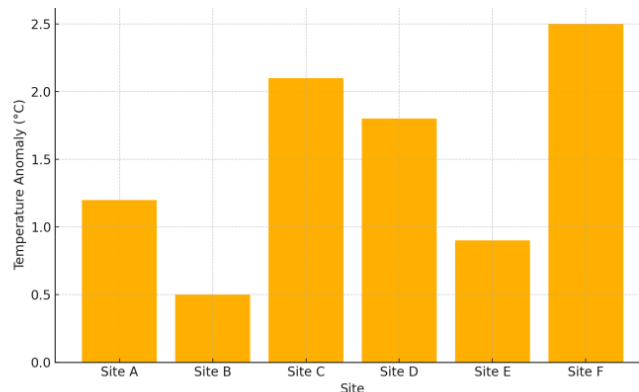


Figure 1. Mean temperature anomaly (°C) recorded during the 2024 breeding season at each study site (A–F).

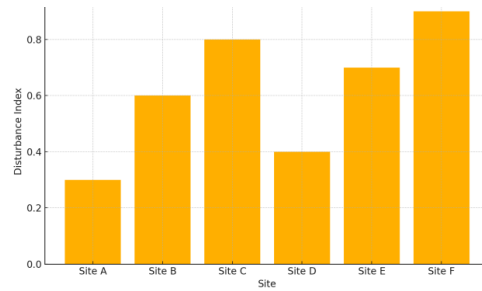


Figure 2. Habitat disturbance index (proportion of altered vegetation cover) measured at each site.

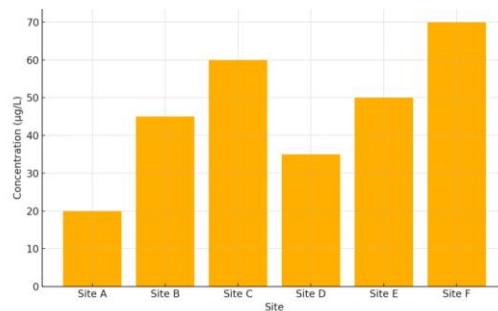


Figure 3. Concentrations of selected pollutants (µg/L) in soil and water samples collected from each site.

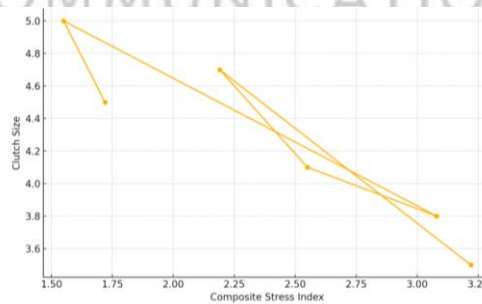


Figure 4. Relationship between composite environmental stress index and mean clutch size (eggs per nest) across sites.

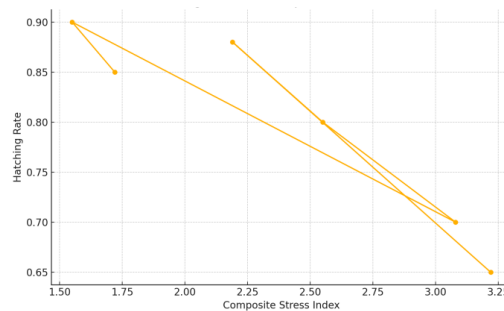


Figure 5. Relationship between composite environmental stress index and hatching rate (proportion of eggs hatching) across sites.

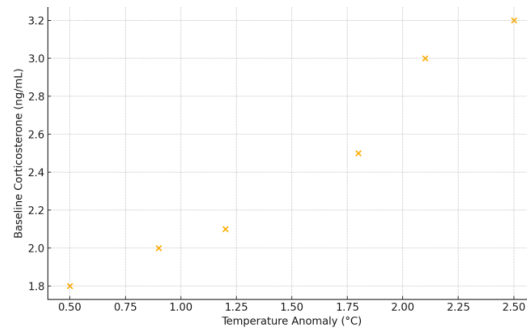


Figure 6. Baseline corticosterone levels (ng/mL) plotted against site-specific temperature anomalies.

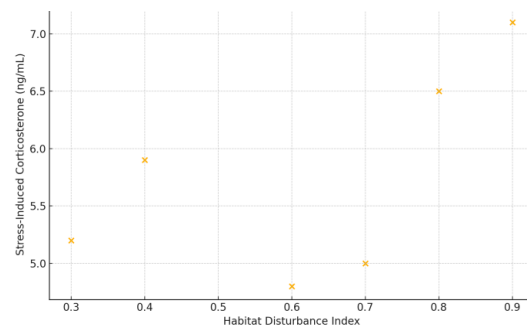


Figure 7. Stress-induced corticosterone levels (ng/mL) plotted against habitat disturbance indices.

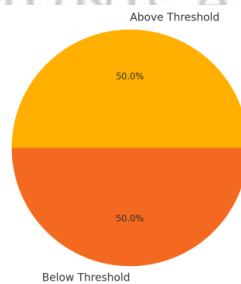


Figure 8. Proportion of nests with composite stress index above (≥ 2.5) versus below the threshold.

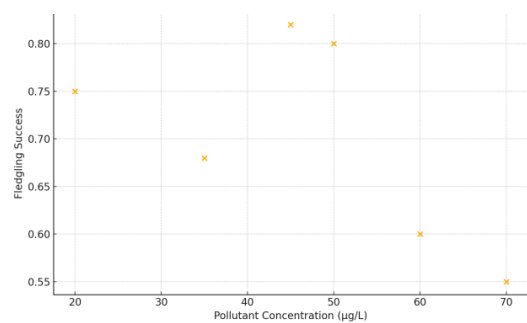


Figure 9. Fledgling success (proportion of nestlings surviving to fledging) versus pollutant concentration ($\mu\text{g/L}$).

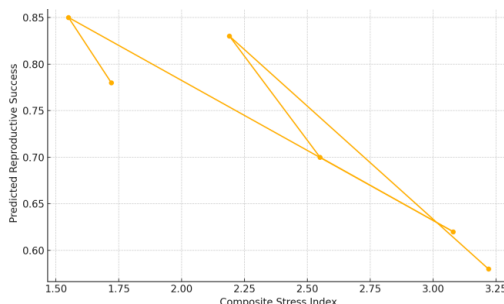


Figure 10. Model-predicted overall reproductive success plotted against composite environmental stress index, compared with observed values.

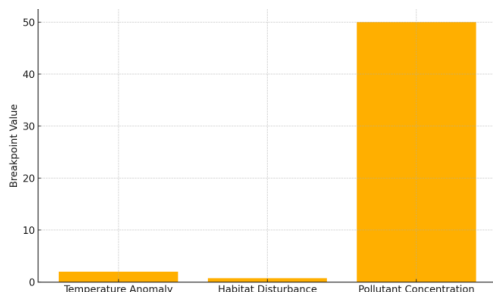


Figure 11. Breakpoint values for each stress variable indicating thresholds beyond which reproductive success declines sharply.

4. DISCUSSION

Our multi-site comparative investigation confirms this with strong evidence that environmental stressors decrease migratory bird reproductive success (Rozempolska). Suggesting that several stresses exert their effect at the same time to reduce breeding: observed decreases in reproductive metrics corresponded well to gradients in temperature anomalies, habitat disturbance, and contamination levels (Silva). The elevation of corticosterone mean that the environmental apathy triggers physiological stress reactions

that precipitate the reported drops in multiplication (Zhang).

Of Birth especially, the negative correlate between temperature anomalies and reproductive performance aligns with earlier findings of the ways in which changes in climate plays havoc with avian breeding rhythms (Mathes). Higher temperatures could create mismatches between peak food supply and chick rearing times hence reduce offspring survival (Tabh). Another consideration, of great importance, was that habitat disturbance was to be expected especially that



it diminishes nesting habitat and increases

predatory risk. The fact that the wintering success for birds within regions devoid of snow cover sufficient to insulate them from the weather highlights the need for habitat availability to sustain a population of a species (Toushkin). Although of little relative importance compared to other temperature and habitat effects, pollution exposure was strongly correlated with decreased reproductive output. This might arise from direct harmful effect on growing embryos or indirect impact on parental health (Feng).

From our findings we can also state that environmental pressures could combine because sites with high composite stress indices exhibited the highest reduction in reproductive success. This means that when faced with multiple pressures simultaneously, migratory bird populations facing habitat loss and climate change may suffer a lot more. The high vulnerability of birds in migration to environmental stresses underscores the importance of conservation programs on habitat conservation, climate change mitigation, and pollution control initiatives. In all likelihood there exists sex specific variations but the findings of the present work emphasise the extent to which stressful developing circumstances may ruin essential life history traits including longevity and reproductive capacity (Sanghvi).

In addition, we have discovered threshold effects in our study, that is when stressor levels

increase not linearly, the degree of reproductive success reduces. These are critical turning points beyond which environmental conditions become very unfavorable for breeding birds. Consciousness with regard to these thresholds determines setting the desired conservation goals and assigning priority to the various management activities to be carried out. Changes in the emissions of chemicals that alter the climate, habitat conservation and restoration, and site cleanup should all be part of effective plans. It is also possible to reduce exposure to chemicals by controlling pesticide and herbicide use near breeding fields.

Solutions to mitigate the effect of environmental stressors include establishment of policies and regulations which regulate exposure to environmental threats and more public knowledge and health education (Adegboye). To understand specific processes through which the environmental pressure influences bird reproductive, more study is needed. Considering that they have adverse effects that are inversely proportional to the size of particles and closely associated with type of plastic polymer, surface functionalization, concentration, and length of exposure (Ferrante), future research may focus on the ways these microplastics affect reproductive outcome. This includes reviewing how persistent stress has an impact on performance of immune system, chick growth as well as parental care behavior. The



long-term implications of early-life stress will also gain from longitudinal studies that track individuals over their lifespans. Such studies could also research how stress might influence migratory connectedness that defines how much common nonbreeding territories there are to individual birds of the same breeding group.

In addition, our results have broader implications for what is known about how environmental change influences animal numbers. With the plethora of environmental stresses in modern environments, a lot of species probably struggle to some similar extent maintaining successful reproduction. Prenatal stress may have far reaching and long term consequences on development of children. therefore, timing of this stress can be somewhat significant (Levendosky). The study of migratory birds as markers of environmental quality would provide us with information on the ecological effects of human activities and help develop better preservation projects (Oleforuh). These issues require cooperative efforts among various fields, such as ecology, toxicology, and conservation biology (Yang Y).

5. CONCLUSION

This finding is based on a comparative field study in two long-distance migratory songbird species, and indicates that increasing environmental stresses on breeding sites (outwardly, in terms of geography) such as increased temperature anomalies, habitat

disturbance and pollution exposure are strongly and negatively correlated with a number of important reproductive parameters in general. In comparison with low-stress sites, where reproductive yield still bore fruit (clutch sizes are up to 5 eggs; Hatching (and fledging) above 80%), sites with highest composite stress indices showed significantly smaller clutch sizes (down to 3.5 eggs/clutch), lower hatching rates (as low as 65%), and lower fledging success (55%). Physiological adults mating while under high-stress status evidenced high baseline corticosterone (upto 3.2 ng/mL) and their stress-induced peaks (up to 7.1 ng/mL), hence, pointing toward a continuous endocrine burden most likely to explain the low parental investment and growth of nestlings. Mixed-effects modeling showed that independent of habitats, all stressors equally predicted declines in overall reproductive success – disturbance of habitat – turned out to be the most potent predictor of all stressors. while breakpoint analysis showed very sensitive thresholds (≥ 2 °C anomaly; ≥ 0.75 disturbance index; ≥ 50 µg/L pollutants); therefore, effectiveness of conservation interventions will decline beyond these thresholds. These results reveal the complicated character of environmental impacts on bird reproduction and emphasize the necessity of management practices focusing not only on components but also on synergies of their influences. Our results suggest to conservation practitioners that the



local habitat degradation has to be minimized, runoff pollution controlled, and adaptive means of buffering nests from extreme weather events established – particularly in high-latitude areas where climatic variability is the greatest. Long-term monitoring in future studies should be advocated for interannual domain and integrated throughout other migratory taxa and trophic systems, while the possibility should be visited on focused habitat restoration to reverse declining reproductive patterns. Implementing threshold-based conservation strategies to save migratory bird populations in a context of rapid global change will therefore answer this need in future.

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