Temporal Trends in Fern Distributions Across Latitudes

Understanding how plant species respond to environmental changes is crucial for predicting future biodiversity patterns. Ferns, a diverse group with a wide distribution, offer a valuable system for studying these shifts, particularly latitudinal movements. By examining such shifts, we can gain insights into broader ecological responses to climate change and human influence. In this study, we investigate whether fern species exhibit latitudinal movements over time, aiming to assess the direction, prevalence, and spatial patterns of these shifts. This work contributes to ongoing efforts to quantify biogeographic change and enhance our understanding of how species spatially reorganize in the face of global change.

Before interpreting the results, it is important to consider the source and structure of the data. Fern observations were collected from a platform that recorded location (latitude and longitude), elevation, and date of observation. Usage of this platform has increased sharply over time, likely introducing sampling bias toward areas with higher human presence or tourism. Additionally, species that are more visually distinctive or familiar are more likely to be recorded. The dataset includes approximately 965,000 observations across various fern species, with about 3,000 unique species of ferns. The majority of ferns are concentrated in Europe and North America (Figure 1). Observations are also present along coastlines in regions such as India and Australia. The most prevalent species, *Pteridium aquilinum*, is predominantly observed in Europe and North America, as shown in Figure 2.

To characterize the typical location of each species, we calculated the mean latitude across all observations for each species, serving as a measure of central latitude. Spatial structure was quantified using the intraclass correlation coefficient (ICC), which represents the proportion of variance in species mean latitudes relative to the total variance in individual latitudes. A high ICC (0.91) suggests that most spatial variation in latitude occurs between species rather than within species. Since longitude is a circular variable, we transformed it using sine and cosine of radian-transformed longitude. We then residualized these trigonometric terms by subtracting the species-specific mean direction, normalizing to unit vectors. This method removes between-species differences in mean longitude, allowing for more accurate estimation of within-species temporal trends.

To investigate latitudinal shifts, we fit linear models predicting latitude as a function of time (day) and other variables using ordinary least squares (OLS) regression for each species. Two models were applied: the first included only main effects, while the second allowed the time trend in mean latitude to vary by longitude. Various diagnostics, including the Likelihood Ratio Test (LRT), confirmed that a cube root transformation was effective for normalizing the data (Figure 3). The significant longitude interactions indicated that models including these interactions were preferable, therefore being the model largely used for this analysis. Additionally, species longitude residuals were used to control for longitudinal effects within each species, enabling more precise interpretation of the day slopes at the species' central longitude. T-scores for the slopes were then converted to Z-scores, with larger sample sizes yielding Z-scores approximating a standard normal distribution under the null hypothesis of no change in latitude. For smaller sample sizes, some uncertainty should be accounted for when converting to Z-scores. A False Discovery Rate (FDR) of 0.1 was used to control for false positives, and the results were analyzed to determine how many species showed evidence of latitudinal movement.

To explore whether Z-scores showed systematic trends with distance from the equator, we plotted the Z-scores against the mean latitude. This analysis allowed us to identify whether the most prevalent species, as well as other fern species, exhibited consistent patterns of latitudinal movement over time. Additionally, these slopes can be plotted against the number of observations, indicating what amount of a certain species typically shows evidence of a change in range.

Upon fitting the final model, which accounted for longitude interactions and residualized longitude effects, we analyzed the Z-scores derived from T-scores. The distribution of Z-scores for ferns (Figure 4) did not follow a standard normal distribution, indicating that some species have shifted their geographic ranges. At a False Discovery Rate of 0.1, we identified 245 fern species exhibiting range shifts. The most prevalent species—*Onoclea sensibilis*, *Polystichum munitum*, and *Matteuccia struthiopteris*—had counts of 41076, 26366, and 16721 observations, respectively. Some species, with as few as 10 observations, also displayed range shifts, suggesting that even small datasets may show evidence of these trends. The map shown in Figure 5 gives us a general idea of where the most prevalent species that showed evidence of latitude change (Onocelea sensibilis) is located. Here, we can see that this species is mostly seen in the western part of Northern America.

Figures 6 and 7 provide further insights into the spatial patterns of these shifts. Figure 6 reveals large Z-scores across all latitudes, with a potential concentration in the northern latitudes of the Northern Hemisphere. This suggests that while latitudinal shifts are occurring across a broad geographic range, the strongest evidence of movement is found in northern regions. Both positive and negative Z-scores were observed at a fairly equal count, indicating that fern species that are shifting in latitude are equally likely to shift towards the poles as they are to move toward the equator.

Figure 7 demonstrates how model power relates to sample size. Larger sample sizes provide greater precision in estimating trends, leading to larger Z-scores for those species. Interestingly, while species with small sample sizes also showed strong evidence of range shifts, the most prevalent species—*Pteridium aquilinum*—did not exhibit evidence of latitudinal movement despite having a large sample size.

The analysis shows that a substantial number of fern species, 245 in total, have shifted their geographic ranges over time. These shifts are observed across a wide range of latitudes, with no single directional trend. The northern latitudes of the Northern Hemisphere exhibit stronger evidence of movement, possibly reflecting more significant ecological changes in these regions. Additionally, there could be other species like Onocelea sensibilis that have a larger presence in the Northern Hemisphere than the Southern Hemisphere. This could further explain the Northern Hemisphere exhibiting stronger evidence of movement. Larger sample sizes generally provided more reliable evidence of latitudinal shifts, though some species with smaller sample sizes also displayed strong evidence of range changes.

Notably, *Pteridium aquilinum*, despite being one of the most commonly observed species, did not show evidence of a latitudinal shift, suggesting that the patterns of geographic movement are species-specific rather than uniform across all ferns. This highlights the complexity of ecological responses to global change, as different species may exhibit distinct patterns of spatial reorganization. This study contributes to our understanding of how fern species are adapting to environmental changes, but the findings suggest that these shifts are nuanced and species-dependent, with patterns that vary across different geographic regions and sample sizes.

Figures

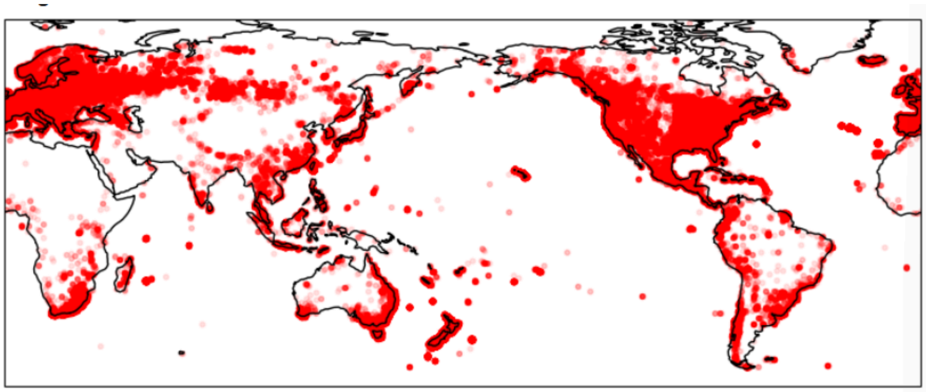

Figure 1: Distribution of all species of Ferns within the dataset

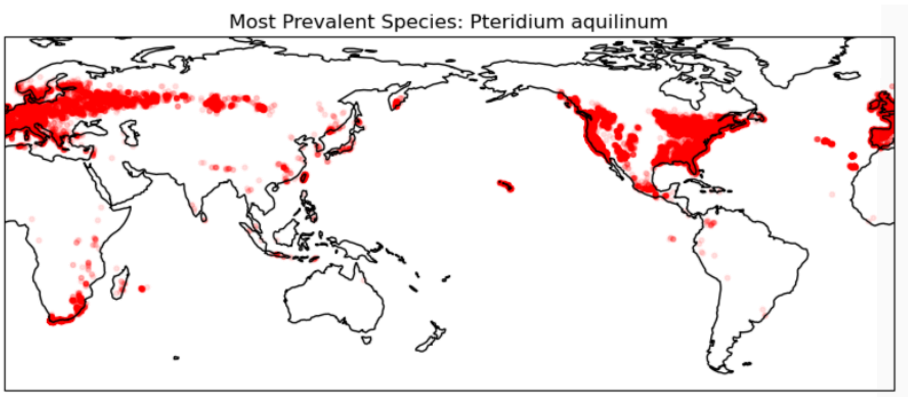

Figure 2: Distribution of Pteridium Aquilinum (the most prevalent species) Ferns within the dataset

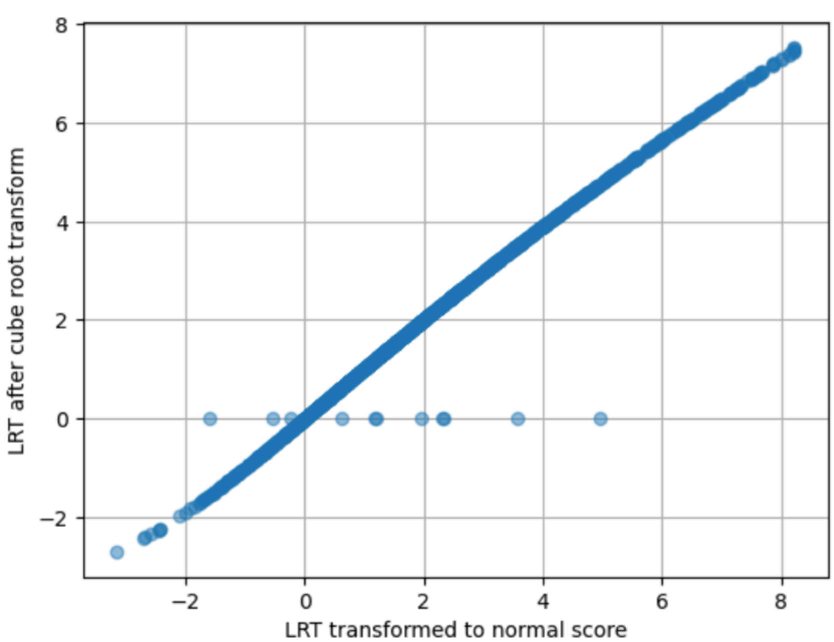

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Figure 3: LRT after cube root transform vs. LRT transformed to normal score.

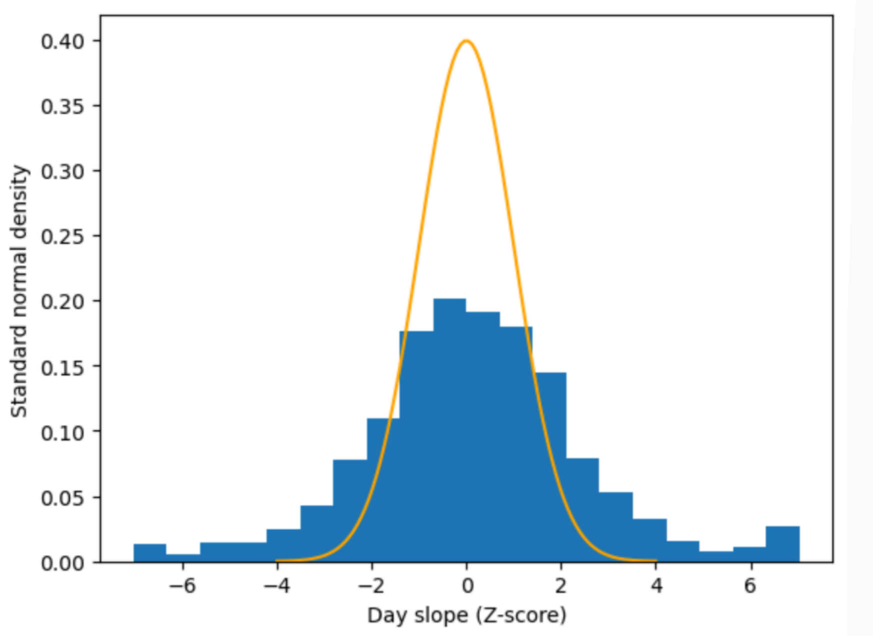

Figure 4: Distribution of day slope Z-scores. The orange curve is what we would expect to see if no species ranges are changing.

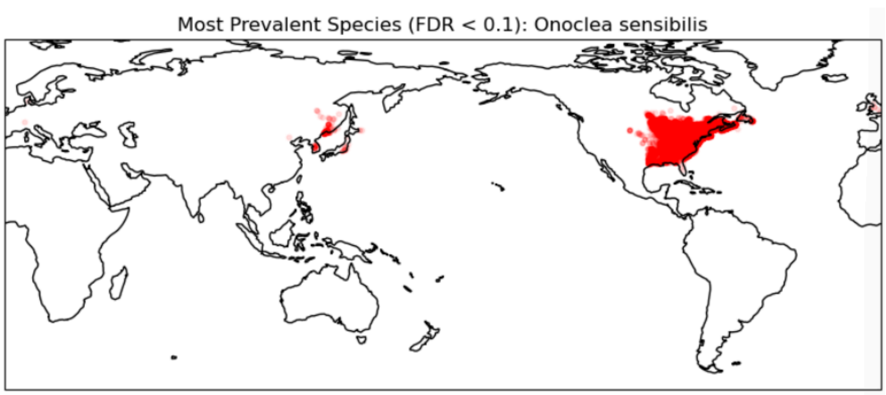

Figure 5: Distribution of the Onoclea Sensibilis, the most prevalent species that has an FDR < 0.1.

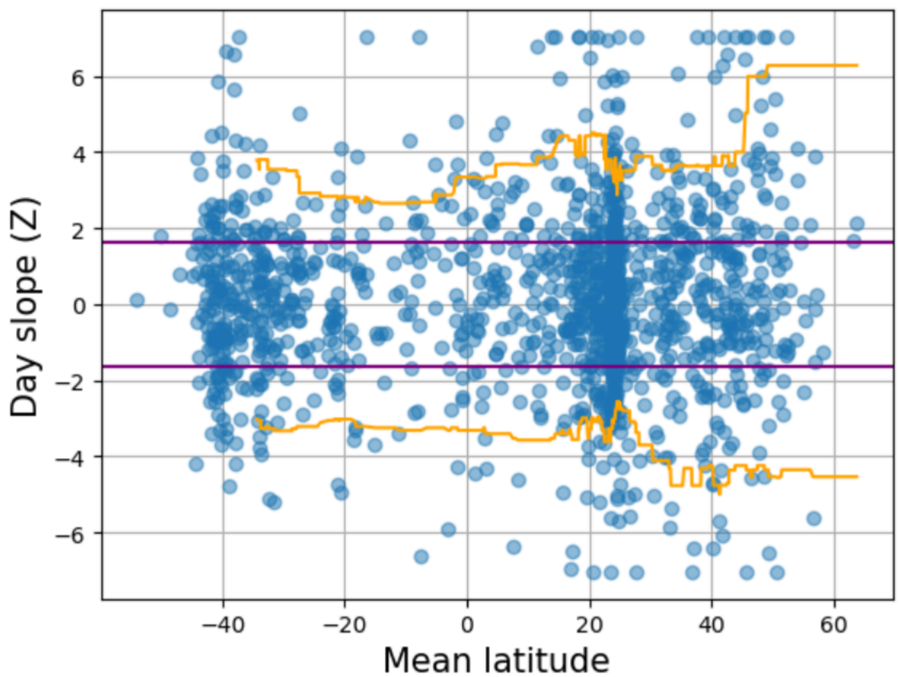

Figure 6: Z-score vs. mean latitude. Orange curves are empirical estimates of the 10th and 90th percentiles of the Z-scores at each fixed latitude; the purple lines are the corresponding reference values under the null hypothesis.

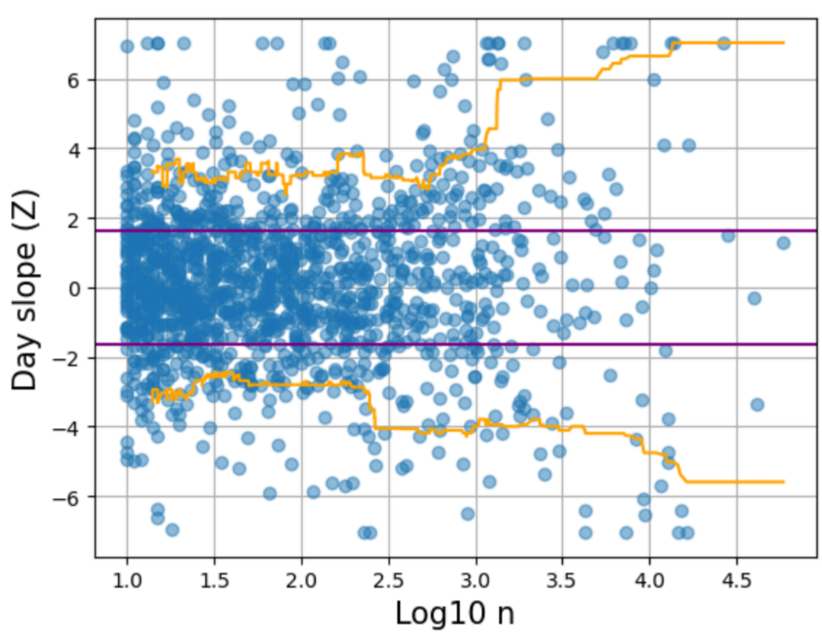

Figure 7: Plot of the slope Z-score against the sample size.

Focus	
Methods	
Writing	
Findings	