Assessing Drought Resilience in Native and Non-Native Tree Species: A Dendroecological Comparison of Douglas Fir, Norway Spruce, and Pedunculate Oak in Southern Germany

Introduction

Climate change intensifies droughts across Europe, impacting forests. Tree-ring analysis helps assess native species' responses to drought and the potential of non-native species as alternatives. In Germany, studies focus on native species like Norway spruce (Picea abies) and Pedunculate oak (Quercus robur). However, the long-established Douglas fir (Pseudotsuga menziesii) offers a unique opportunity for comparison (Speer, 2010) [1].

Motivation: Understanding drought responses is critical for climate-resilient forestry. Native species may struggle under future conditions, while Douglas fir could offer better drought tolerance. This study predicts forest vulnerability, identifies climate-suited species, and evaluates Douglas fir as a potential alternative.

Research Questions

1. How do Norway spruce, Pedunculate oak, and Douglas fir differ in resilience to the 1976 and 2003 droughts?
2. What are the long-term climatic influences on their growth?
3. Does Douglas fir show higher drought resilience, supporting its role as a climate-adapted species?

Methods & Statistics

This study uses dendroecological methods to analyze species-specific drought resilience and long-term climatic influences on tree growth. The approach ensures reproducibility for other researchers with basic dendroecology training.

1. **Data Collection and Preprocessing**
   - Tree-ring width data from Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziesii*), and Pedunculate oak (*Quercus robur*) were collected from Oehberg, Northern Bavaria.
   - Data was processed using the dplR package, and tree-level mean series were computed for each species to ensure reliable growth estimates.
2. **Detrending and Standardization**
   - Raw ring-width series were detrended using a cubic spline (32-year window) to remove non-climatic growth trends.

- Chronologies were created using standardized ring-width indices (RWI).

Figures 1 illustrate the spaghetti plot between detrended and original tree mean values for

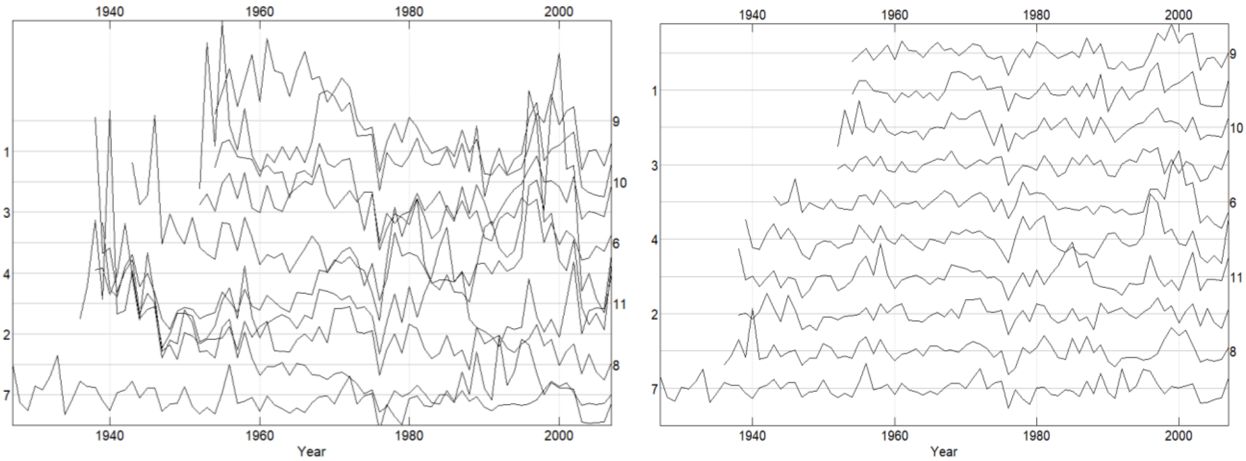


Figure 1

spruce.

3. **Growth Resilience Analysis (1976 & 2003 Droughts)**

   The Lloret et al. (2011) resilience framework, implemented via the pointRes package, was used to compute resilience as post-drought growth relative to pre-drought growth. Resilience indices were compared across species using box plots, while Shapiro-Wilk tests assessed normality and Wilcoxon rank-sum tests evaluated interspecies differences (Lloret et al., 2011) [2].

4. **Long-Term Climate Limitations (Climate-Growth Relationships)**

   Climate data (temperature and precipitation, 1901–2021) were integrated with tree-ring chronologies to analyze climate-growth relationships. Linear regressions provided initial insights, while response function analysis using the treeclim package evaluated long-term climate influences. Moving-window analysis (20-year windows, 3-year offsets) captured temporal variations in climate sensitivity, and dendro linear models (dlm) quantified the impact of precipitation on growth (Kim et al., 2013) [3].

5. **Statistical Validation and Interpretation**

   - R-squared values and p-values evaluated model performance.
   - Climate-growth relationships were compared across species, highlighting Douglas fir's potential as a drought-resilient alternative.

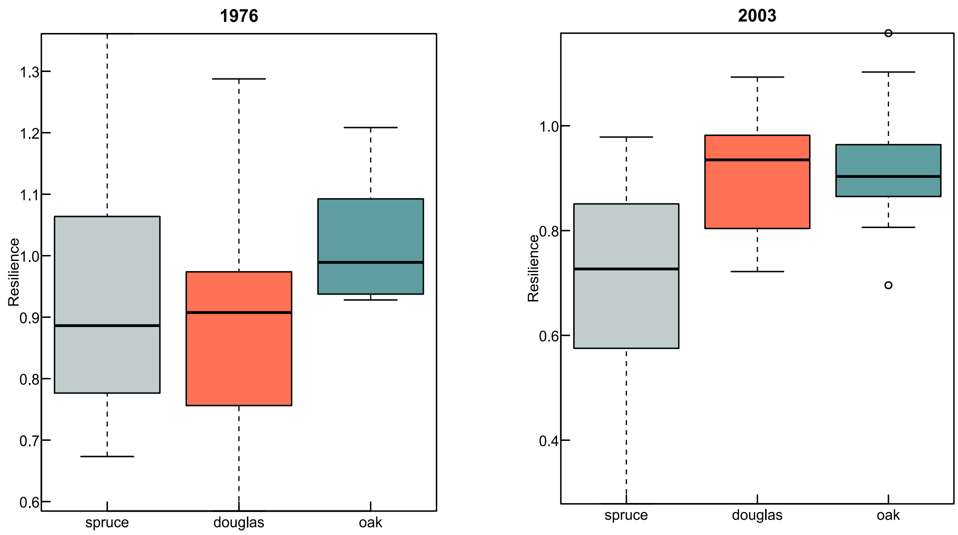
Summary of Results

The boxplots (Figure 2) highlight the differences in resilience among the three species for both drought years:

Growth Resilience Analysis (1976 & 2003 Droughts)

Pedunculate oak showed the highest resilience in both the 1976 and 2003 droughts, with a consistently high median and narrow variability, indicating strong adaptability. Norway spruce had moderate

resilience in 1976 but showed a decline in 2003, suggesting increasing vulnerability to drought. Douglas fir exhibited the lowest resilience in 1976 but improved by 2003, indicating potential



adaptability over time.

Overall, oak proved the most drought-resistant, Douglas fir showed some improvement, and spruce demonstrated declining resilience, raising concerns about its future viability under increasing drought stress.

Shapiro-Wilk Normality Tests

A Shapiro test is performed For all three species, the resilience indices are **not normally distributed** (p-value < 0.05 for all cases). Hence, non-parametric statistical tests (Wilcoxon rank-sum test) were applied.

Wilcoxon Rank-Sum Tests

1976 Drought:

- **Spruce vs. Douglas Fir:** No significant difference in resilience (p = 1.00).
- **Spruce vs. Oak:** Marginal difference (p = 0.089), indicating that Oak tends to be more resilient than Spruce, though not statistically significant.
- **Douglas Fir vs. Oak:** No significant difference (p = 0.165), suggesting similar resilience between the two species.

2003 Drought:

- **Spruce vs. Douglas Fir:** Significant difference (p = 0.023), with Douglas Fir showing higher resilience than Spruce.
- **Spruce vs. Oak:** Significant difference (p = 0.023), with Oak being more resilient than Spruce.
- **Douglas Fir vs. Oak:** No significant difference (p = 0.853), suggesting similar resilience between these two species in 2003.

Pedunculate oak showed the highest and most consistent drought resilience, while Norway spruce demonstrated declining resilience over time, raising concerns about its vulnerability to drought. Douglas fir, initially less resilient, showed improvement by 2003, suggesting potential adaptability to changing climatic conditions.

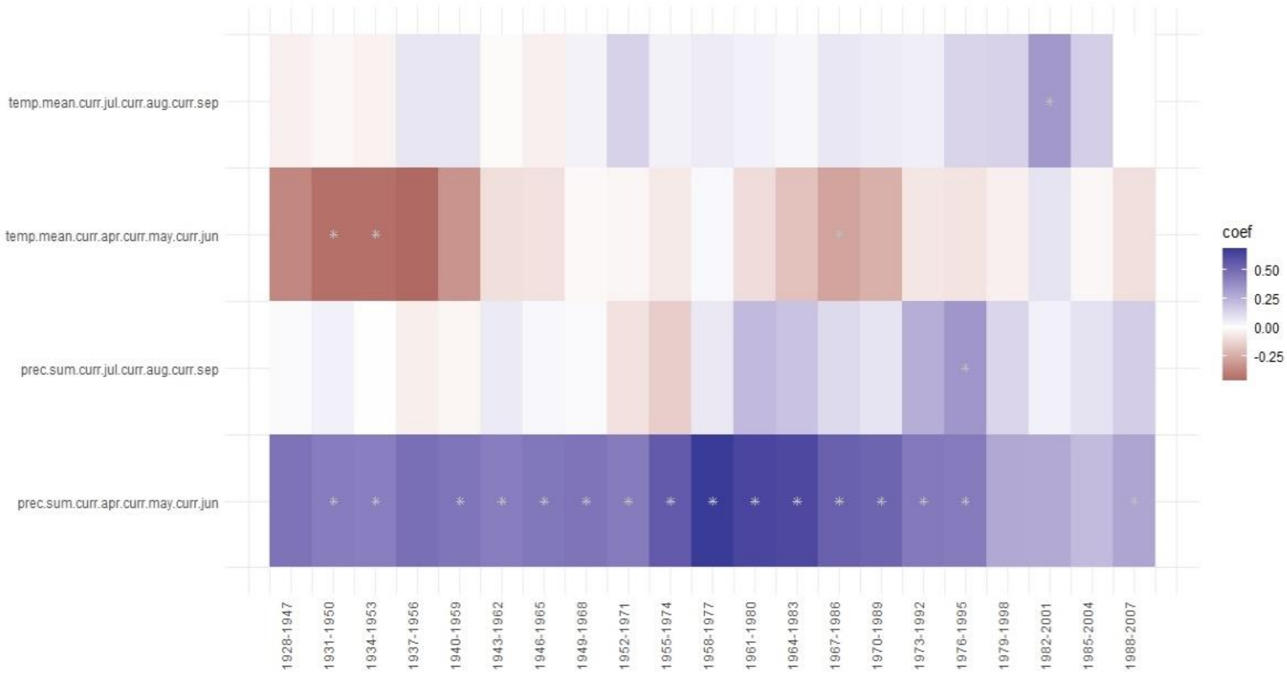
Analysis of Long-Term Climate Limitations (Response Functions)

Overview of Outputs

The dynamic calibration plots for the three species (Douglas fir, Norway spruce, Pedunculate oak) reveal the correlation between tree-ring indices and climatic variables (precipitation and temperature) over time using moving-window analysis. Significant correlations are marked with asterisks (*), while the color intensity indicates the strength and direction of the correlation.

Key Observations by Species

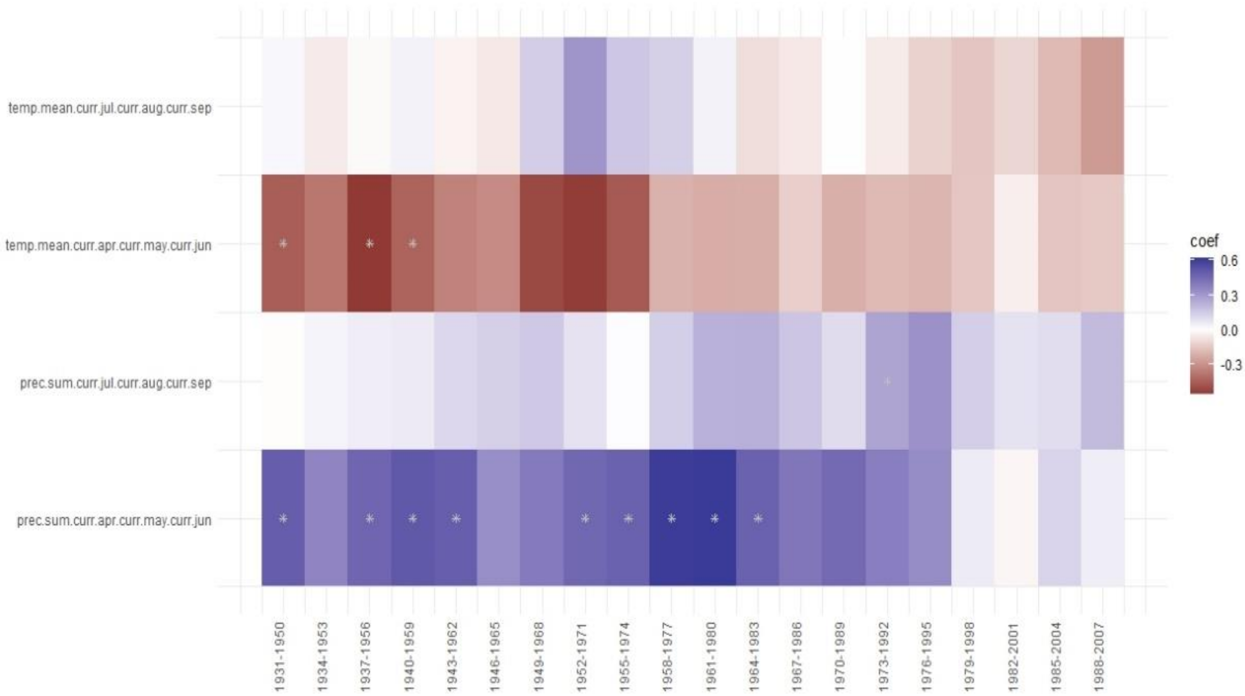
1. **Douglas Fir**



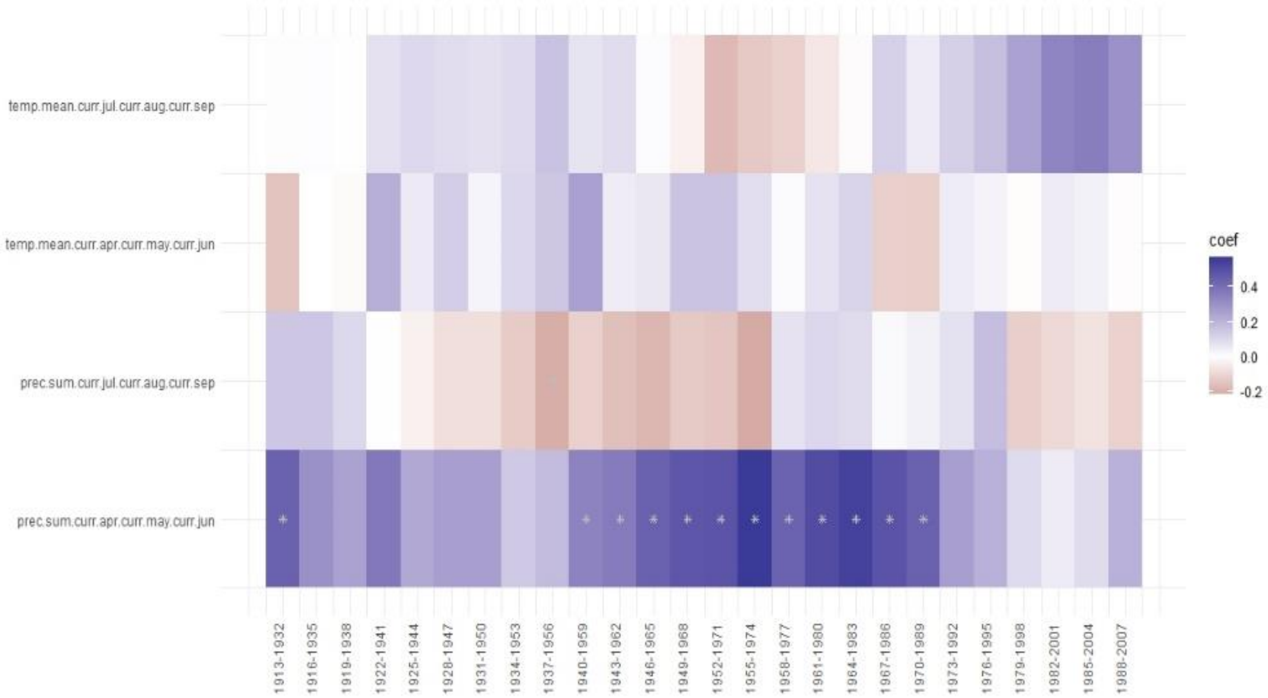
Douglas fir (my_calib1) exhibits growth sensitivity to climatic variables. Spring temperature (April–June) shows predominantly negative correlations, particularly in earlier decades, suggesting adverse effects on growth, with significant correlations mid-century. Summer temperature (July–September) also trends negative but less consistently. Spring precipitation (April–June) reveals strong positive correlations, with significant periods highlighting its importance for growth, while late summer precipitation (July–September) shows moderate positive correlations, indicating secondary support for growth.

2. Norway Spruce

Norway spruce exhibits stronger negative correlations with spring temperatures (April–June) compared to Douglas fir, especially in earlier decades, reflecting greater sensitivity to warm spring conditions that may limit growth. Summer temperatures (July–September) also show negative correlations, though less pronounced, indicating secondary sensitivity to heat. Positive correlations with spring precipitation (April–June) are significant, particularly mid-century, emphasizing its importance for growth. Unlike Douglas fir, spruce demonstrates stronger correlations with late-summer rainfall (July–September), suggesting a prolonged dependency on water availability throughout the growing season.



3. Pedunculate Oak



The sensitivity of oak growth to climatic variables reveals distinct patterns. During April–June, temperature exhibits moderate negative correlations, though these are less pronounced than those observed in spruce and Douglas fir, indicating that oak is relatively less sensitive to spring heat compared to the conifer species. For July–September, a mix of negative and neutral correlations suggests low sensitivity of oak growth to summer temperatures. In contrast, precipitation during April–June shows positive correlations, particularly significant during mid-century and later decades, underscoring the importance of spring precipitation in supporting oak growth, similar to the conifers. Finally, July–September precipitation demonstrates strong positive correlations, with numerous significant windows, indicating that oak relies more heavily on late-summer precipitation than the conifer species.

Comparison Between Species

Pedunculate oak demonstrates the greatest climate resilience, with low sensitivity to temperature and strong reliance on spring and late-summer precipitation, reflecting its adaptability to extended growth periods and water availability. Norway spruce, in contrast, shows high sensitivity to spring and summer temperatures and strong precipitation dependency, making it the most vulnerable to climate change. Douglas fir displays intermediate adaptability, relying on spring precipitation and showing moderate temperature sensitivity, making it suitable for regions with stable rainfall but potentially vulnerable to warming trends.

Pedunculate oak stands out as the most adaptable species under future climatic extremes. Douglas fir offers moderate resilience but depends on consistent spring rainfall. Norway spruce, with its high sensitivity to both temperature and precipitation, is the least climate-resilient and most at risk under climate change.

(Analysis of Dendro Linear Models (DLM) is documented in APPENDIX 1).

Implications

This study underscores the importance of selecting climate-resilient tree species to mitigate the impacts of anthropogenic climate change on forest ecosystems. Pedunculate oak should be prioritized in reforestation and forest adaptation strategies for its exceptional drought tolerance and adaptability. Douglas fir offers moderate resilience and can serve as a secondary option, especially in areas with consistent spring precipitation. Norway spruce, however, is increasingly unsuitable for regions facing frequent droughts and warming trends, necessitating a shift in forest composition to ensure long-term ecosystem stability.

Future research should focus on continuous monitoring of these species' growth responses under evolving climatic conditions to refine species selection and improve forest management practices in the face of climate change (Lloret et al., 2011) [2]; (Speer, 2010) [1].

References

[1] Speer, James, *Fundamentals ofTree-Ring Research*. University of Arizona Press.

[2] F. Lloret, E. G. Keeling, and A. Sala, "Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests," *Oikos*, vol. 120, no. 12, pp. 1909–1920, Dec. 2011, doi: 10.1111/j.1600-0706.2011.19372.x.

[3] B.-S. Kim, H.-S. Kim, and S.-H. Min, "Hurst's Memory for Chaotic, Tree Ring, and SOI Series," *Applied Mathematics*, vol. 5, no. 1, Art. no. 1, Dec. 2013, doi: 10.4236/am.2014.51019.

APPENDIX 1

Analysis of Dendro Linear Models (DLM)

The DLM models for **spruce**, **Douglas fir**, and **oak** examine the relationship between tree-ring width indices (chronologies) and summer precipitation (June, July, and August). Here's an analysis aligned with the task of computing long-term climate limitations and comparing species.

Spruce (Norway Spruce)

- **Adjusted R-squared**: 0.2414 (24.14% variability explained).
- **Significant Predictors**:
  - **June Precipitation**: Positive and highly significant (**$p < 0.001$**) with an estimate of **0.00242**.
  - **July Precipitation**: Positive and significant (**$p = 0.036$**) with an estimate of **0.00114**.
  - **August Precipitation**: Positive but marginally significant (**$p = 0.067$**) with an estimate of **0.00124**.
- **Interpretation**:
  - Spruce growth is **positively correlated with summer precipitation**, particularly in June and July.
  - Precipitation during August is less critical but still shows some impact on growth.
  - The model explains a moderate portion of the growth variability (24.14%), highlighting spruce's reliance on water availability during early-to-mid summer.

Douglas Fir

- **Adjusted R-squared**: 0.1727 (17.27% variability explained).
- **Significant Predictors**:
  - **June Precipitation**: Positive and highly significant (**$p < 0.001$**) with an estimate of **0.00155**.
  - **July Precipitation**: Positive and significant (**$p = 0.02$**) with an estimate of **0.00089**.

- **August Precipitation**: Not significant (**p = 0.474**).

- **Interpretation**:
  - Douglas fir shows a positive response to **early summer precipitation (June)**, with a weaker response to July precipitation.
  - August precipitation has negligible influence, suggesting Douglas fir primarily depends on water during the early summer growth phase.
  - The model explains less variability compared to spruce, indicating additional factors may influence Douglas fir growth.

Oak (Pedunculate Oak)

- **Adjusted R-squared**: 0.1017 (10.17% variability explained).
- **Significant Predictors**:
  - **June Precipitation**: Positive and highly significant (**p < 0.001**) with an estimate of **0.00216**.
  - **July Precipitation**: Not significant (**p = 0.426**).
  - **August Precipitation**: Not significant (**p = 0.241**).
- **Interpretation**:
  - Oak growth is **highly dependent on June precipitation**, while July and August precipitation have negligible effects.
  - The model explains the least variability among the species (10.17%), suggesting that oak growth is less dependent on summer precipitation overall.

Comparison of Species

1. **Sensitivity to Summer Precipitation**:
   - **Spruce** shows the strongest and most consistent positive response to summer precipitation (June and July).
   - **Douglas fir** relies on early summer precipitation (June) but has a weaker response overall.
   - **Oak** is highly dependent on June precipitation but is less sensitive to late summer rainfall.
2. **Model Fit (Adjusted R-squared)**:
   - Spruce (24.14%) > Douglas fir (17.27%) > Oak (10.17%).

    - This indicates that summer precipitation explains a greater proportion of variability in spruce growth compared to the other species.

3. **Implications for Climate Limitations**:
    - **Spruce**: Highly dependent on consistent summer precipitation, making it vulnerable to drought conditions.
    - **Douglas fir**: Moderately dependent on early summer precipitation, suggesting it may tolerate mid-to-late summer drought better than spruce.
    - **Oak**: Less sensitive to summer precipitation, indicating it is more adaptable to varying precipitation patterns.

Conclusion

- **Spruce** shows the highest sensitivity to summer precipitation, particularly in June and July, indicating strong dependence and vulnerability to water stress during early-to-mid summer.
- **Douglas fir** also relies on summer precipitation but less strongly, making it a potentially more drought-tolerant species compared to spruce.
- **Oak** exhibits resilience with limited dependence on summer precipitation, suggesting it may be the most adaptable species to changing precipitation patterns.

This analysis aligns with the task of determining long-term climate limitations and comparing the growth responses of different species.