A millennium-long blue ring record in bristlecone pine (*Pinus longaeva* D.K. Bailey) - establishment and paleoclimatic interpretation

Abstract

The study of past climates, known as paleoclimatology, plays a crucial role in understanding the Earth's climate system and predicting future climate changes. Within this field, dendroclimatology - using tree rings to infer past climatic conditions - has proven to be a particularly valuable method. Tree rings provide annual records of climate variability, and their width, density, and composition can reflect past temperature, precipitation, and other environmental factors.

Bristlecone pine (*Pinus longaeva*), known for its longevity and resilience in harsh climates grows, at high elevations in the White Mountains of California and other high mountain ranges of Nevada and Utah, making it a particularly sensitive indicator of environmental changes. This sensitivity, coupled with its long lifespan, makes it an ideal candidate for studying past climate variability over millennia. Upper tree line populations correlate with temperature, while lower tree line stands offer a resource for precipitation reconstructions.

The discovery of "blue rings" in this and other species opens possibilities to add a new layer of information to climate reconstructions derived from these trees.

The formation of blue rings (BRs) is a temperature-dependent process in which cooler temperatures during and after the late growing season disrupt the lignification of cell walls, resulting in underlignified cells that appear bluish when stained with Safranine and Astrablue. To address the need for more precise tools to reconstruct past climate conditions, particularly short-term and subtle temperature variations that are not well captured by other proxies, this study developed the use of blue rings as a sensitive thermal indicator in bristlecone pine, arguing that they may offer a more accurate proxy for past cooling episodes than traditional tree ring indicators.

Previous studies have established a strong connection between growth minima, frost rings, and growing season cooling and frost episodes. This connection has been particularly useful in reconstructing volcanic eruptive histories causing cooling episodes.

However, traditional dendroclimatological methods have limitations in their ability to capture short-term and subtle climatic fluctuations. While frost rings provide valuable information, they are less sensitive to milder cooling events or late-season temperature drops. Tree ring widths, on the other hand, are less capable to accurately capture interannual and intra-annual temperature variations due to strong autocorrelation resulting from biological memory, aggregating climate signals from the entire growing season and even from previous seasons. Tree ring width-based temperature reconstructions frequently exhibit a lagged and smoothed-out climate response to abrupt cooling following volcanic eruptions compared to other proxies. This research addresses the need for a more sensitive and reliable proxy that can capture these subtle, high-frequency variations, thereby improving the accuracy of paleoclimatic reconstructions, complementing traditional dendroclimatological proxies.

Specifically, this study investigates whether blue rings in bristlecone pine can serve as a more sensitive proxy for late-season cooling events by developing a comprehensive blue ring time series from 83 cores and covering almost two millennia. By comparing blue ring occurrence with available climatic data from 1895 to 2008, we first investigate the connection between temperature, topography and blue ring formation. Further, across the timespan of the past eleven centuries, we explore the association between blue rings and historical volcanic eruptions, and analyze how the information contained in blue rings is distinct from, and complementary to frost ring, TRW, and MXD-based paleoclimate inferences.

We find that blue rings in Bristlecone pines are significantly influenced by late-season temperature drops, particularly in September. However, apart from the influence of September, our findings also reveal that blue rings form as a result of a more complex interplay of climatic factors, with lower temperatures in April, June, and August and higher temperatures in February and October also playing a role. The occurrence and intensity of blue rings decrease gradually with elevation below the upper tree line, indicating that topography and elevation modulate their formation.

We established a strong, statistically significant connection between BR formation and volcanic activity. These results suggest a causal link between volcanic eruptions and BR formation through volcanically induced cooling with tropical eruptions showing the strongest correlation.

Not all BR signals are linked to significant volcanic eruptions, just as not all RW and/or MXD minima correspond to known volcanic events. This is because not every cold summer in a particular location can be attributed to volcanic activity, and similarly, not all eruptions lead to cooler summers. While BRs offer a sensitive record of cooling episodes, they can also be a noisy proxy, with many low BR signal years reflecting localized cold snaps rather than large-scale cooling.

Our results demonstrate that blue rings tend to form more often in wider or neutral rings and frequently precede negative pointer years or growth minima. This suggests that BRs can provide valuable insights into late-season or post-growing season cooling events, which would no longer affect the ring width of that year. Longer cooling periods, such as those linked to climatically effective volcanic eruptions, can impact climatic conditions after the completion of radial growth and into the following seasons. As a result, while these events may cause a delayed response in ring widths, BRs can signal the onset of such events earlier. Moreover, BRs are better suited than ring widths to record cooling episodes, as they form when a sudden temperature drop halts the lignification process, leaving a permanent mark of underlignified cells. In contrast, ring widths are influenced by biological memory and autocorrelation, which can delay the cooling evidence and smooth out its magnitude.

Finally, we demonstrate how a multiproxy approach - integrating frost rings, ring widths, maximum latewood density (MXD), ice-core data, and BRs - can enhance our understanding of the climate system's response to volcanic eruptions.

Overall, the study expands the understanding of the factors that influence blue ring formation. While previous research has suggested a link between blue rings and temperature, this study provides a more detailed analysis of the specific climatic conditions that lead to their formation. By using a large dataset of tree cores and applying statistical modeling techniques, the research offers a comprehensive assessment of the factors that influence blue ring formation, including temperature, elevation, and topography. Although earlier studies established a tentative connection between blue ring formation and volcanic activity, we reinforced this connection with a larger dataset and longer timeline, and highlighted specific nuances that BRs can contribute to our knowledge of the timing and spatial extent of climatic consequences of specific eruptions.

The use of blue rings as a proxy for past cooling events could enhance the accuracy of climate reconstructions improving our understanding of how climate has changed over millennia providing an additional layer of information about abrupt short-term events that might otherwise not be captured by tree ring-based reconstructions. BRs could also help in untangling the complex interactions between volcanoes, climate, and human activity at sub-annual resolution. This is because societal resilience or vulnerability is highly reliant on agricultural productivity, which can be influenced by short-term weather extremes that are usually not reflected in the traditional TRW and MXD chronologies. This better understanding of past climate variability could lead to better predictions of future climate trends, particularly in relation to volcanic activity and other large-scale climate forcings, with possible abrupt consequences for societies.