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Shifting Climate Sensitivities, Shifting Paradigms: Tree-Ring Science in a Dynamic World

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The uniformitarian principle is assumed in all dendrochronological inferences, and, as in all sciences of the past, if this principle does not hold, no conclusions regarding the past can be made.
—Harold C. Fritts 1976, *Tree Rings and Climate*

Dendrochronology, the science of tree-ring dating, has been used to study numerous types of environmental and social phenomena, from rainfall in the Amazon basin (Brienen et al. 2012) to the historical timber trade in Northern Europe (Bridge 2012). The annual growth rings of trees are of particular value as natural archives, or sources of information about past environments, because ring width, structure, and chemical composition are all influenced by the environmental conditions under which the tree ring was formed. Using large datasets that document tree growth patterns over centuries to millennia, dendroclimatologists attempt to reconstruct environmental conditions (e.g. temperature, precipitation, stream flow, snow pack, wildfires, and hurricanes) of the past. Because of this versatility, tree rings and the researchers that analyze them play crucial roles in contextualizing climate change and rendering

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© The Author(s) 2018
R. Lave et al. (eds.), *The Palgrave Handbook of Critical Physical Geography*,
https://doi.org/10.1007/978-3-319-71461-5_10

it visible and comprehensible to policymakers and the public. Deep knowledge of past relationships between tree growth and environmental conditions also allows researchers to investigate questions about the future of forest ecosystems in a warming world. The scholarly contributions of tree-ring scientists, however, have been contested, and over the past two decades tree-ring based climate research has witnessed controversy (e.g. McIntyre and McKitrick 2005; Wahl and Ammann 2007; Mann et al. 2012; Anchukaitis et al. 2012).

In this chapter, we explore tree-ring science as a field of study that exemplifies both the already existing practices of Critical Physical Geography (CPG) "in the wild" and the potential for even more integrative, reflexive, and engaged scholarship. As authors, we present original research on tree growth-climate interactions but also consider the science of dendrochronology itself as our object of analysis. In other words, we are concerned both with material relationships among climate, trees, forests, and people *and* with the ways in which scientific ideas about these relationships are being tackled, challenged, and reformulated. We specifically interrogate the principle of uniformitarianism that undergirds tree-ring-based climate research and call attention to a growing body of work that finds tree growth-climate relationships that fluctuate over time.

Inspired by CPG's call to integrate diverse methodologies and ways of knowing, we bring together quantitative analyses of relationships between climate and tree growth in Great Smoky Mountains National Park (GSMNP), Tennessee, with qualitative data on the practices, opinions, and perspectives of tree-ring scientists. Unless otherwise noted, all quoted material is excerpted from responses to an anonymous survey of tree-ring scientists ($n = 48$) administered by the first author in 2016. We employ multiple methods here not to triangulate results or scrutinize a singular research object but to bring into conversation strands of scholarship that might otherwise be pursued separately, placed in different academic books or journals, presented in separate conference sessions, and read by audiences with little overlap. This integration allows us to contribute to scholarship on tree growth and climate while simultaneously considering how this body of knowledge shapes and is shaped by the politics and discourses of climate change and the social identities of tree-ring researchers.

Ultimately, we find that temporal instability in climate-tree growth relationships might be addressed by fostering what Jasanoff (2003, 2007) calls "technologies of humility," in which scientists are compelled to continually "reflect on the sources of ambiguity, indeterminacy, and complexity" (Jasanoff 2007, p. 33) in their research and to recognize that even the most ostensibly robust scientific work is insufficient to achieve generalizable solutions to pressing socioecological concerns such as climate change. The survey results discussed here indicate that a culture of humility is already being actively fostered by many tree-ring scientists, but that significant obstacles remain to developing and implementing new patterns of thought, methods, and technologies.

Tree Rings, Climate Science, and Controversy

Extracting climate information from tree rings seems relatively straightforward at first glance: long growing seasons and abundant energy and water tend to coincide with wide annual rings, while seasons in which resources are more limited are marked by narrow annual rings (Speer 2010). But the apparent simplicity that makes tree-ring research so compelling and accessible belies the methodological complexity of climate reconstruction and the changing assumptions that underpin it. Over the past two decades, the methods for achieving tree ring-based climate reconstructions have come under heightened scrutiny by climate change skeptics and deniers, with highly publicized controversies materializing around the "hockey stick" graph (Mann et al. 1998, 1999) published in the Intergovernmental Panel on Climate Change's (IPCC) assessment reports and the 2009 hacking of a server of the University of East Anglia's Climatic Research Unit ("Climategate") (Holliman 2011; Anderegg and Goldsmith 2014). Such controversies highlight the high political stakes of climate reconstruction and the powerful but precarious position of tree-ring scientists as scientific authorities on climate. As one researcher and survey respondent noted, tree ring-based climate reconstructions "seem to have a target on their back."

Even as dendroclimatology has weathered a storm of attacks from outside the field, it has also experienced a gradual upwelling of concern from within regarding the reliability of reconstructions and the assumption of consistent, linear relationships between tree growth and climate variables over time. Climate reconstruction is made possible through a number of assumptions and principles, two of the most basic being the principles of uniformitarianism and limiting factors. Together, these principles assert that tree growth is limited by the factor in shortest supply relative to demand (e.g. moisture, energy, sunlight, etc.), and crucially, that the factors that limited tree growth during the past century also limited tree growth in prior centuries and will likely continue to limit tree growth in the future. While it has long been known that growth is a function of many interacting factors other than just climate (e.g. genetics, age, competition, and various disturbance processes), the general consensus in tree-ring science has been that, at sites where growth is strongly affected by climate, the climate-tree growth relationship can be isolated and the influences of other factors can be minimized to enhance the climate signal (i.e. increase the signal-to-noise ratio). After identifying and isolating the relationship between climate and tree growth in the historical period for which climate data are available, scientists then use tree-ring data to reconstruct how climate has varied over a longer time scale, before the collection of instrumental data. In short, climate reconstruction from tree-ring proxy data has proceeded under the assumption that an essential climate-tree growth relationship exists and can be isolated for a given species at a given site that functions relatively consistently over time.

Recently, however, findings of time-varying responses by trees to climate have shown stable, linear relationships between tree growth and climate variables to be less common than previously believed. The identification of a "divergence problem" in dendroclimatology in the mid- to the late 1990s drew attention to the lack of temporal stability in climate-tree growth relationships. "Divergence" refers to a weakening of the relationship between temperatures and tree growth beginning in the 1960–1970s at high northern latitude and high-elevation sites, where trees are generally expected to be more responsive to changes in temperature than moisture (D'Arrigo et al. 2008). At many sites, trees that previously responded positively to temperature appear no longer to be temperature-sensitive (Jacoby and D'Arrigo 1995; Briffa et al. 1998; Barber et al. 2000; Driscoll et al. 2005). Instrumental temperature records and the predicted temperature values derived from tree-ring chronologies begin to diverge around the mid-twentieth century, with actual temperatures increasing while tree growth has remained stable or declined.

The past decade has seen a surge of published research on the temporal stability of climate-tree growth relationships, with a large number of studies finding unstable relationships for numerous tree species worldwide. These species include white spruce (*Picea glauca*) in the Yukon Territory (Porter and Pisaric 2011), Alaska yellow cedar (*Xanthocyparis nootkatensis*) in southern Alaska (Wiles et al. 2012), pines and European larch (*Larix decidua*) in the European Alps (Carrer and Urbinati 2006; Oberhuber et al. 2008), mountain hemlock (*Tsuga mertensiana*) in the North Cascades (Marcinkowski et al. 2015), eastern hemlock (*Tsuga canadensis*) in the central Appalachians (Saladyga and Maxwell 2015), and hardwoods in the central USA (Maxwell et al. 2016). No consensus, however, has been found regarding the cause(s) of shifting climate-tree growth relationships, the degree to which such instability is the norm, and the implications that such findings have for climate reconstruction, tree-ring science, and models of ecosystem dynamics in a warming world. Some cases of instability are thought to be directly or indirectly related to anthropogenic warming over the past half-century, while other studies have found multi-century patterns of instability that appear unrelated to recent climatic changes (Frank et al. 2007). Research has also linked the changing sensitivities of trees to localized anthropogenic forcings. In Bavaria, for example, changes in the ways silver firs respond to climate appear to be related to local SO_2 emissions (Wilson and Elling 2004). Still others suggest that instability may be a product of the methodological choices (e.g. artifacts from imprecise detrending) made by researchers rather than a material phenomenon inherent within the affected trees (D'Arrigo et al. 2008; Esper and Frank 2009). More research is needed, however, to determine the frequency, extent, and causes of unstable climate-tree growth relationships, and many tree-ring researchers are pursuing this line of inquiry.

Findings of time-varying responses by trees to climate are not new (Cook and Johnson 1989; Van Deusen 1990), but this recent emphasis calls into question the basic assumption of uniformitarianism in all tree ring-based climate reconstructions. The accuracy and reliability of reconstructions are dependent on relatively consistent climate-growth relationships over time, especially during the twentieth century when tree-ring data are calibrated with instrumental climate data. Hence, the implications of temporal instability in climate-growth relationships are potentially vast. If trees do not consistently respond through time to one or more climate variable, knowledge of past climates might be compromised. Tree-ring science has thus come to a crossroads. The assumptions that underpin dendroclimatology are increasingly being interrogated, and the precepts upon which the field was established are yielding to a new formulation of climate-tree growth relationships as fluid and non-linear. It is at this crossroads that our chapter is situated.

Climate Sensitivity of Pines in Great Smoky Mountains National Park, Tennessee

We now turn to our research on climate-growth relationships in mid-elevation pine-oak woodlands in GSMNP. A conservation priority in the southern Appalachians, pine-oak forests have declined over the past century due to a combination of factors that include fire exclusion, southern pine beetle (*Dendroctonus frontalis*) outbreaks, climate change, and timber harvesting (Harrod et al. 2000; South and Buckner 2003; Dale et al. 2010; Coyle et al. 2015). Using tree-ring data, we analyze the responses of pines to climate over the twentieth century, with the goal of understanding which specific climatic factors drive pine growth and if these factors have remained consistently significant over the twentieth century. We have two broad aims. First, we demonstrate how changes in climate-growth relationships are analyzed and how "instability" comes to be defined and recognized. Second, we use this case to reflect on some of the possible mechanisms for temporal instability in climate-tree growth relationships. A definitive explanation for the shifts we identify is certainly beyond the scope of the chapter. We suggest, however, that the responses of pines growing in GSMNP to climate are unstable and were derived through interactions via both positive and negative biotic and abiotic feedbacks, including physiological mechanisms, effects of micro- and macro-topography, possible factors related to anthropogenic activities, and climate state. This has significant normative implications, which we explore here as well.

Data and Methods

We assess the climate sensitivity of pines using a composite tree-ring chronology of pines growing at mid-elevation sites (400–750 m) in GSMNP (Fig. 10.1). To build this chronology we targeted mature canopy-dominant shortleaf pines (*Pinus echinata*) growing in pine-oak woodlands on xeric

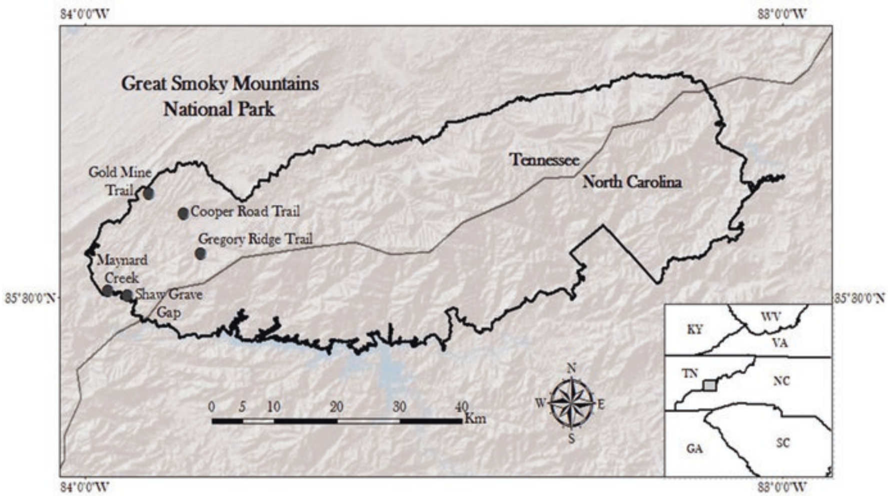

Fig. 10.1 Map of study sites in Great Smoky Mountains National Park, Tennessee. The tree-ring chronology we analyze is a composite of five individual chronologies developed in the westernmost portion of the park

south- or southwest-facing slopes in the westernmost region of GSMNP. Because shortleaf pine is known to hybridize in the wild with pitch pine (*Pinus rigida*) (Smouse and Saylor 1973), we also sampled hybrids and pitch pine individuals at one of the five sites.

The composite tree-ring chronology was built from five individual site chronologies, encompassing a total of 390 core samples from 245 trees. Two cores were extracted from each tree at breast height (1.3 m), air-dried, and sanded using standard dendrochronological methods (Orvis and Grissino-Mayer 2002). Ring widths were measured to 0.001 mm on a Velmex measuring system interfaced with Measure J2X software. We cross-dated all tree rings to ensure the correct calendar year was assigned to every tree ring by identifying common patterns of wide and narrow rings among the tree-ring series using the list method (Yamaguchi 1991), and then statistically verified our cross dating using the program COFECHA (Holmes 1983; Grissino-Mayer 2001). All ring-width series were then detrended in the program ARSTAN (Cook 1985) to allow the tree-ring series to be averaged into a single index chronology. We chose relatively conservative forms of standardization, using negative exponential curves or linear regression lines with the goal of removing age-related growth trends but retaining possible decadal-scale climate signals in the data.

We analyzed the relationship between tree growth and climate over the twentieth century using historical precipitation, temperature, and Palmer Drought Severity Index (PDSI) data from the National Centers for Environmental Information (NCEI). For precipitation and PDSI, we used the NCEI Eastern Tennessee divisional data over the period 1895 to 2007, the last year corresponding to the last year of the tree-ring data. For temperature, we analyzed pine sensitivity to monthly average minimum temperature rather than mean temperature because preliminary analyses found that minimum temperatures were strongly correlated with shortleaf pine growth in the southern Appalachians. We obtained instrumental minimum temperature records (1910–2007) from a single weather station (McGhee Tyson Airport, Alcoa, Tennessee), as this station began recording daily minimum temperatures earlier than other stations in the region and is the nearest weather station offering 100% data coverage.

We calculated correlations between annual tree growth and monthly climate parameters, spanning from June of the previous growing season to October of the current growing season, recognizing that growth may be influenced by previous year conditions as well as current season conditions (Fritts 1976; Speer 2010). To test the possible changing relationship between pine growth and climate over time, we performed moving correlation analysis at

45-year intervals (e.g. 1910–1954, 1911–1955, etc.) using the program DendroClim2002 (Biondi and Waikul 2004). This technique indicates the periods during which climate variables were significantly correlated with tree growth. Using the program treeclim (Zang and Biondi 2015; version 2.0.0 released 5 September 2016), we then plotted the results of moving correlation analysis on correlation evolution graphs to visually highlight periods in which significant shifts occurred in the climate-tree growth relationship. In all analyses, statistical significance is reported at $p < 0.05$.

We emphasize that the methods we employed have become standard procedures in tree-ring science over the past decade because these new technologies can account for the dynamic nature in tree growth responses to climate over time. DendroClim2002 and its companion program treeclim were created by and for tree-ring scientists in response to concerns about temporal (in)stability and represent significant additions to dendroclimatological research practices since the mid- to the late 1990s. The software offers a user-friendly way to test and visualize climate responses over time and has helped researchers to recognize and contend with complexity and instability in climate-growth relationships. Both programs have added a higher level of accuracy in the selection of climate variables to be reconstructed.

Our survey results reflect these perceptions well. Of our 48 respondents, 35 (72.9%) believe that temporal instability affects the reliability of climate reconstructions, and many report that they have altered their own research practices in light of this issue. For example, one researcher noted that (s)he abandoned conducting a climate reconstruction from a high-elevation chronology in the western USA after performing moving correlation analysis and finding that relationships among climate and growth appeared highly unstable throughout the short period of instrumental data. Another response echoed this, stating that "if the DendroClim correlation graphs aren't a big straight band of color across the twentieth century, the chronology should absolutely not be used for climate reconstruction." For some respondents, testing temporal stability also served to demonstrate the credibility of tree-ring science in the broader climate change research and policy community, thus preventing future attacks by climate change deniers: "if analyses are not done properly, things like 'hide the decline' (Climategate) could happen again." In our analyses, we perform moving correlation analysis in DendroClim2002 not to reconstruct climate or demonstrate credibility but to illuminate the "ragged fringes" of scientific understandings of climate-growth relationships (Jasanoff 2003, p. 227).

Major Findings

Our analyses indicate that rather than being limited by a single factor, annual growth of pines in GSMNP is limited by multiple, interacting climatic variables. We identified significant positive correlations between growth and three groupings of climatic variables: (a) average minimum temperature for three winter months (January, February, and March) as well as October of the current growing season (Fig. 10.2a); (b) precipitation for February, May, and

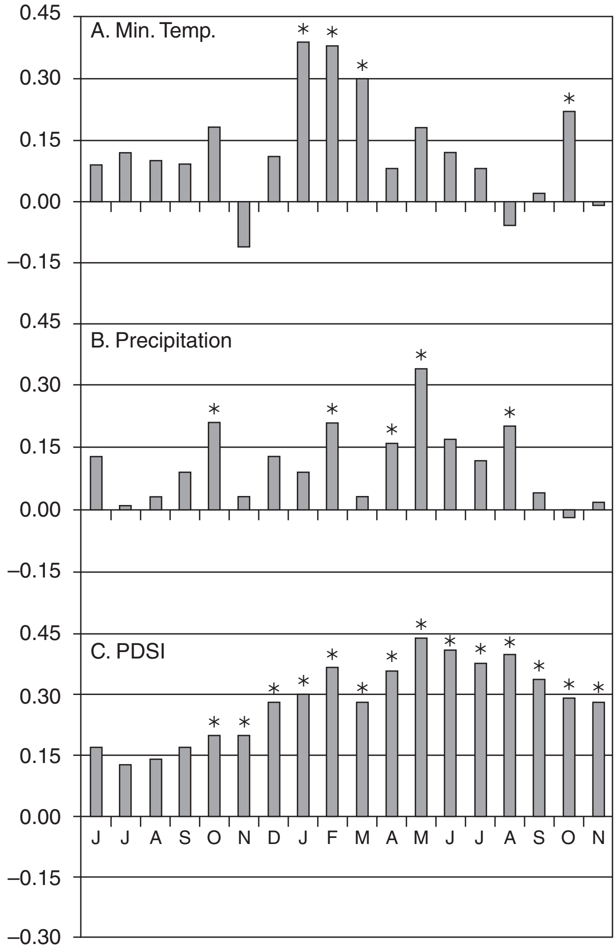

Fig. 10.2 Bootstrapped correlation coefficients between the composite chronology and monthly (**a**) average minimum temperature, (**b**) precipitation, and (**c**) PDSI, from previous June (left) to current growing season November (right). Asterisks indicate statistically significant correlations ($p < 0.05$)

August of the current growing season and October of the previous growing season (Fig. 10.2b); and (c) moisture availability (via PDSI) throughout the current growing season (Fig. 10.2c). Looking for seasonal groupings of significant monthly parameters, we conclude that low winter temperatures limit annual radial growth of shortleaf and pitch pine in GSMNP during our study period.

This response to winter minimum temperature is noteworthy because other studies in the southeastern USA have found mid-elevation conifers to be predominantly precipitation or moisture sensitive (Friend and Hafley 1989; Copenheaver et al. 2002). Although some studies have noted a weak winter temperature signal (Stambaugh and Guyette 2004) or even a negative summer temperature signal (Grissino-Mayer and Butler 1993), no prior studies have investigated the effects of *minimum* temperatures on pine growth in the southeastern USA. In our analysis, we found that when winter minimum temperatures are warmer, radial growth tends to be greater in the following growing season. Warmer winters may allow pines to photosynthesize during winter thaws or break dormancy earlier in the spring, leading to above average annual growth. Minimum temperatures may be more important than average temperatures because a certain temperature threshold must be reached for the trees to remain photosynthetically active or break dormancy (Perry 1971).

We also noted a significant positive correlation between growth and growing season PDSI, suggesting that long-term moisture availability may be more important for pine growth than total precipitation, emphasizing the important role of temperature and soil conditions working together with rainfall to moderate tree growth. In general, years with high annual growth corresponded with low drought stress and abundant soil moisture. These conditions are particularly beneficial in the late spring and summer months, when southern pines put on most of their annual cambial growth (Zahner 1962; Dougherty et al. 1994; Emhart et al. 2006).

Despite the significant relationships identified between pine growth and monthly climate, the sensitivity of pine growth to climate has fluctuated over the past century (Fig. 10.3). Moving correlation analysis performed over 45-year windows indicated that no single monthly climate parameter was significantly related to annual growth for the entire duration of the study period (1910–2007). PDSI during February is the one month that came closest to being temporally stable for the full length of the 98-year-long period we examined, but showed a weakened relationship for 45-year periods ending around 1962 to 1972 (Fig. 10.3c). Because trees did not respond consistently to one or more dominant environmental factor over time, the factors that

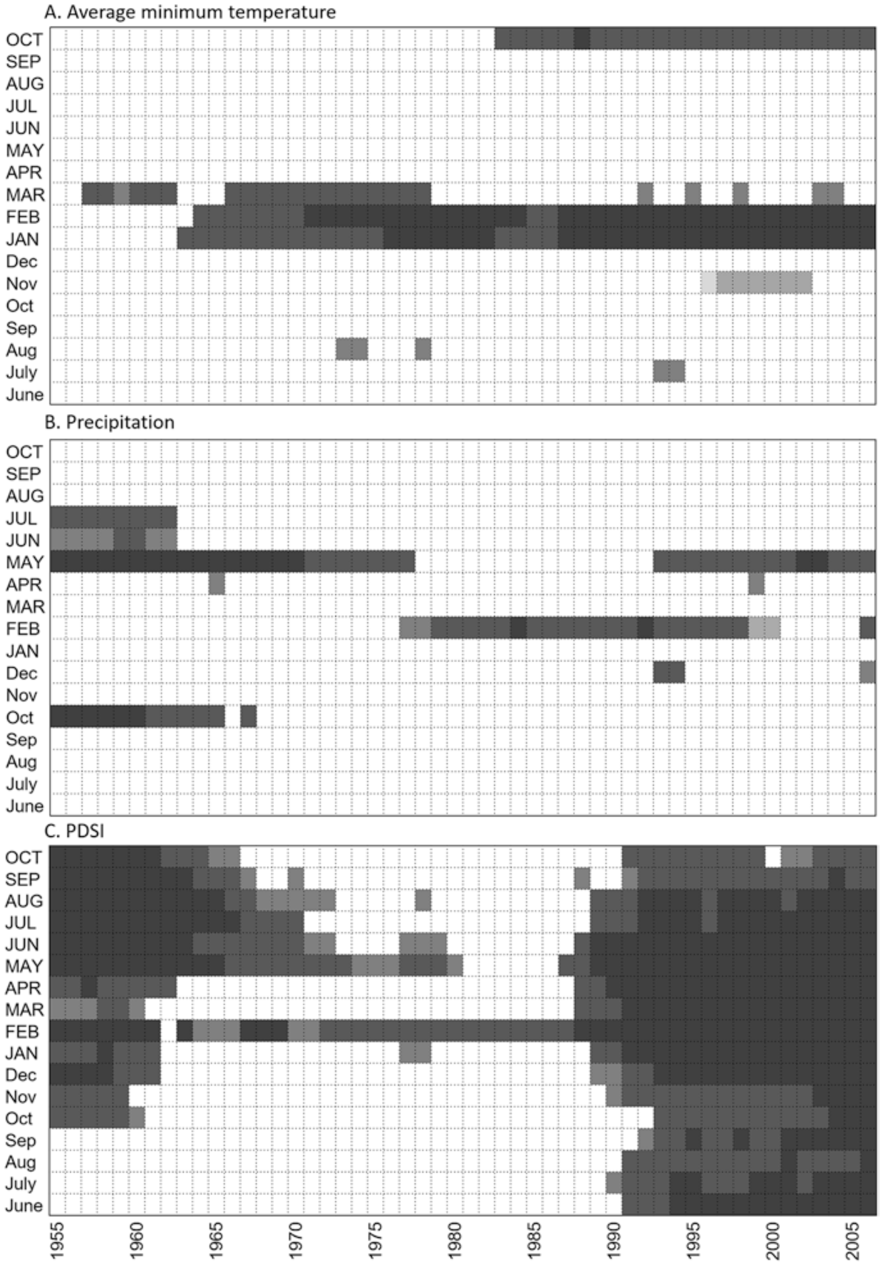

Fig. 10.3 Results of moving correlation analysis between the composite tree-ring chronology and monthly climate: (**a**) average minimum temperature, (**b**) precipitation, and (**c**) PDSI, from previous June (bottom of y-axis) to October of the current growing season (top of y-axis). Years shown are the last years of the 45-year moving intervals, that is, correlations plotted for 2005 represent correlations calculated from 1961 to 2005. All shading indicates statistically significant correlations. The darker the shading, the stronger the correlation ($p < 0.05$)

limit growth of pines in GSMNP in one year, decade, or even century, should not be assumed to limit growth in another period.

Before mid-twentieth century, winter minimum temperatures appear to have had little influence on pine growth, but when data after 1964 are added to our analysis, the relationship between winter temperature and growth becomes significant (Fig. 10.3a). Similarly, current October temperature was significantly positively correlated with growth in the initial monthly correlation analysis (Fig. 10.2a), but the moving analysis shows that the correlation was not significant until the latter part of the century (Fig. 10.3a). Had our analyses stopped before 1983, the results would suggest no relationship between October temperature and growth. Precipitation during May, June, and July precipitation were also inconsistently correlated to growth (Fig. 10.3b). Had we simply used the results of the correlation analysis, we would have inferred that May precipitation was a likely candidate for reconstruction, but the relationship between pine growth and May precipitation was statistically insignificant for 45-year periods ending from 1978 to 1992. While the pine response to winter temperature has strengthened over the twentieth century, the response to growing season precipitation actually weakened. The most dramatic changes occurred in the relationship between pine growth and drought (as measured by PDSI), when correlations dropped precipitously in the 45-year periods ending 1972 to 1990 but increased again ca. 1990.

Inspection of the changes in climate-tree growth relationships over time via correlation evolution graphs was particularly instructive (Fig. 10.4). We observed that the responses to average minimum temperatures were split among positive and negative correlations for 45-year periods ending in 1955, but by the 45-year period ending in 2007, nearly all monthly responses were positive or near positive (Fig. 10.4a), with the exception of the strong negative correlation with previous November temperature (Fig. 10.2a). This demonstrates an overall strengthening of the pine growth response to temperatures over the twentieth and early twenty-first centuries. We also identified key transition periods of temporal instability. For example, a perturbation in the climate-pine growth relationship occurred in the 45-year periods ending in the late 1950s, seen primarily in the weakening response to PDSI (Fig. 10.4c) as well as strengthening response to minimum temperatures (Fig. 10.4a). The relationship between pine growth and PDSI remained weak until the 45-year periods ending in the mid- to late 1980s when the correlations increased dramatically, stabilizing in the early 1990s to correlations similar to those we observed for the most recent 45-year period ending in 2007. Curiously, no overall trend or transition periods could be identified in the response by pines

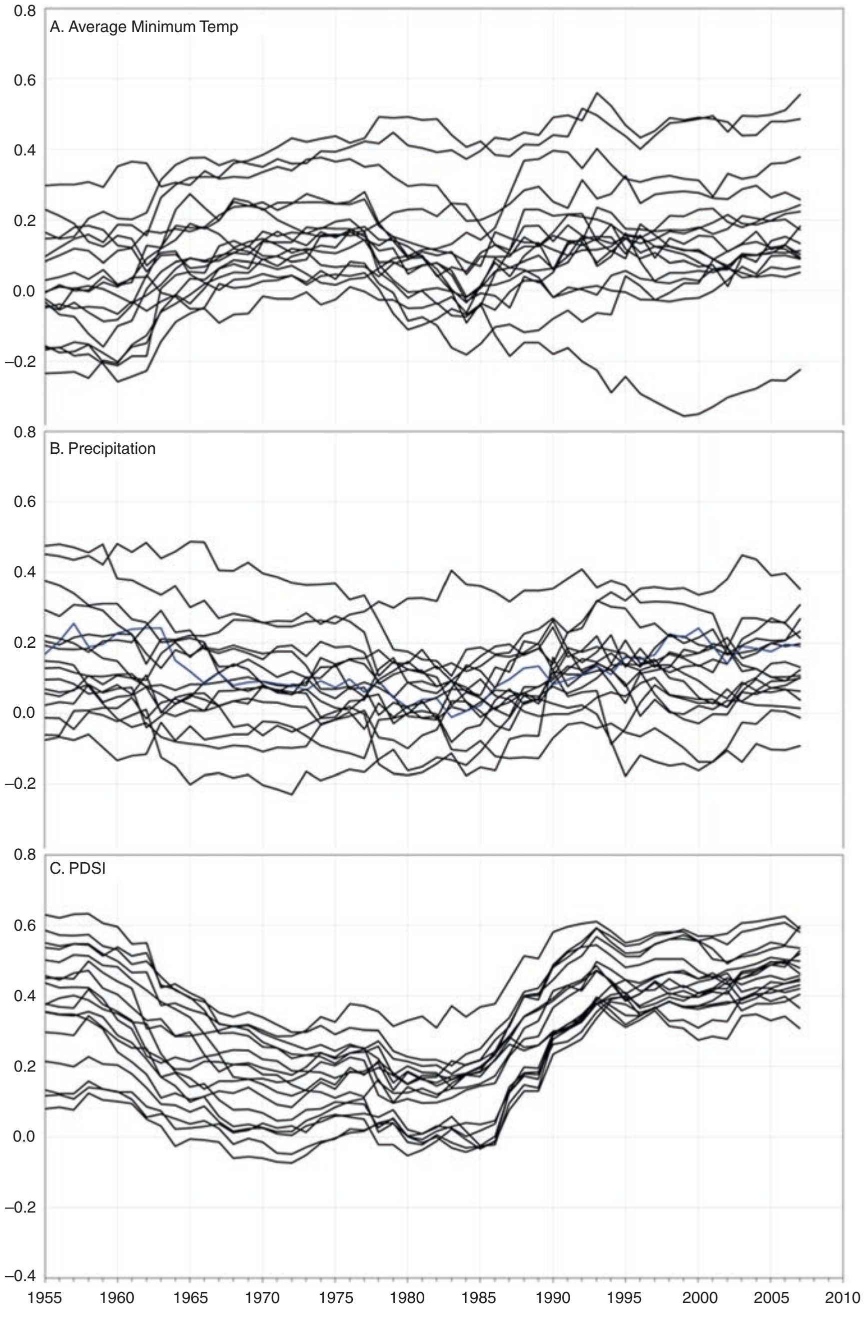

Fig. 10.4 Correlation evolution graphs showing evolving correlation patterns over time, beginning with the 1910–1955 base interval, for all months of the three climate variables analyzed in this study. The coefficients are plotted according to the last year of the 45-year moving interval, that is, correlations plotted for 2005 represent correlations calculated from 1961 to 2005

to precipitation (Fig. 10.4b). Based on these findings, we classify the climate-tree growth relationship in this study as unstable.

Causes and Implications of Instability of Climate Responses in GSMNP and Beyond

Our designation of this relationship, however, raises questions about what constitutes and causes such instability of climate responses, both for our site specifically and for climate and trees more generally. At present, dendrochronologists have not established a standard protocol for distinguishing between a "stable" climate response and an "unstable" one. Our designation is based on the fact that the parameters most strongly related to growth change over time, but other definitions of instability are possible as well. Several survey responses address this issue:

> In my opinion, the most urgent change to be made is a more statistically founded discussion of what instability actually means, and how to quantify and compare it.

> [H]ow do we determine what level of inconsistency is acceptable for a chronology to be used for a reconstruction? And furthermore, how do we communicate the complexity of all of this to the public without allowing a few people to pick this up and run with it to discredit climate science?

Our survey revealed a wide range of views exist as to the extent of temporal instability in tree growth-climate relationships. While some responses suggest that growth-climate relationships are inherently variable because "trees are not thermometers," and "a linear, univariate relationship for a biological organism is a silly assumption," others imply that "trees probably still react to climate in the same way as in previous millennia," but that "what has changed is rather the yearly 'composition' of the climate." A subset of those that attribute temporal instability to climatic changes view the issue as possibly unique to the Anthropocene and a function of anthropogenic climate change. In this view, if climate was relatively stable, we would expect the responses of trees to climate to be stable as well.

This range of perspectives is also found in the published literature, where numerous causal mechanisms have been put forth to explain apparent instability in the sensitivities of trees to climate. Possible causes include methodological factors such as the reliability of weather station data (Frank et al. 2007) and the type of detrending pursued in chronology development

(D'Arrigo et al. 2004), as well as factors considered "internal" to the tree, such as tree genetics and aging (Szeicz and MacDonald 1994). Other hypothesized mechanisms focus on climate itself, attributing shifts in sensitivity to climatic extremes or regime shifts in climate, possibly linked to oceanic-atmospheric climate oscillations or recent anthropogenic warming. For example, extreme high temperatures may induce moisture stress, causing trees to exhibit a stronger response to moisture than temperature. Furthermore, trees may exhibit complex non-linear or threshold responses. For example, trees that responded positively to temperature in the past may begin to respond to factors other than temperature once a certain temperature threshold is passed. Still other factors that may contribute to temporal instability include acclimation of trees to changing conditions, atmospheric pollution, insect outbreaks, logging, fire (and fire suppression), and land use change.

While we do not aim to and indeed cannot identify one or more definitive causes for instability in pine responses to climate in GSMNP, here we expand on the ways in which intertwined human and ecological processes influence tree sensitivity to climate. We posit that tree sensitivity to climate should be understood as a relational and contingent outcome—not inherent to a given site, species, or climate regime, but produced through a suite of interacting factors. This conceptualization reinterprets the principle of limiting factors, one of the established principles of the field. Instead of focusing attention primarily on climate parameters as limiting factors, researchers also must consider how tree-climate relationships are influenced by land use history and changes in ecosystem structure, composition, and function caused by both human and natural disturbances. Such factors do not merely confound or disturb an underlying climate response but may indeed enable it in the first place.

Recent tree-ring studies support this conceptualization of responses to climate as a relational outcome, influenced by clear cutting (White et al. 2014), earthworm invasion (Larson et al. 2010), landscape development (Wilmking and Myers-Smith 2008), and anthropogenic changes to the water table (Smiljanić et al. 2014). In North Carolina, for example, red spruce experienced a shift in sensitivity to temperature post 1930, coinciding with clear-cut harvesting (White et al. 2014). In the north central USA, the climate responses by hardwoods have been altered by invasive earthworms that dramatically reduce leaf litter on the forest floor (Larson et al. 2010). In survey responses, dendroecologists note that oftentimes "basic ecological knowledge is not incorporated into dendroclimatology," and that "most ecologists have no problem" understanding time-varying responses to climate by trees, because they recognize that limiting factors are variable over time and space. Together, these studies and responses remind us that tree-climate relationships are embedded in broader landscapes, and that considering these landscapes and their dynamics can aid in understanding how tree growth responds variably to climate.

Southern Appalachian pine-oak woodlands, including the stands we sampled, have changed dramatically over the past two centuries. Low intensity, frequent fire played a significant role in shaping the landscape through a combination of natural and anthropogenic ignitions (Grissino-Mayer 2016). From the mid-nineteenth to early twentieth centuries, Euro-American settlers used fire to clear land for grazing, agriculture, and timber harvesting (Pyle 1988), but fire has been actively suppressed since ca. 1940 (Grissino-Mayer 2016). The forests of the westernmost portion of GSMNP were a mosaic of open woodlands and closed canopy forests at the start of the twentieth century (Ayres and Ashe 1905) but have changed in composition and structure between the 1920s and today. In particular, fire-tolerant pines are failing to regenerate since ca. 1940, while both canopy density and basal area have increased (Harrod et al. 1998; Harrod and White 1999). In our study sites, mesic, fire-intolerant species such as red maple (*Acer rubrum*), eastern white pine (*Pinus strobus*), and mountain laurel (*Kalmia latifolia*) comprised the understory, with very few shortleaf and pitch pines present as seedlings or saplings, suggesting an ongoing shift in species composition.

Over the past century, the pine-oak woodlands of GSMNP have experienced a number of other changes as well. Leaf litter and duff have increased at many sites, as the exclusion of fire has allowed the surface layer of soil organic matter to thicken over time rather than be consumed by fire as fuel. The chestnut blight (*Cryphonectria parasitica*) also affected the region, wiping out all chestnut trees (*Castanea dentata*) and dramatically changing the composition of the forests in GSMNP. At our study sites, chestnut seedlings and saplings were present in the understory growing from old root stock and stumps, indicating the former presence of chestnuts. Our sites also showed evidence of widespread southern pine beetle infestation and mortality, a native beetle that has contributed to declines of pine timberland throughout the southeastern USA. The weakening relationship of pine growth with precipitation in the mid-twentieth century, and strengthening relationship to winter temperature, may indeed be related to the changing ecosystem of which they are part, and in particular the build-up of leaf litter and duff, the establishment and growth of shade-tolerant and fire-sensitive species, the park's policy of fire suppression, and other major disturbances such as the southern pine beetle outbreak. By thickening the surface layer of soils and increasing the density of understory vegetation, such factors may have also moderated the effect of drought on pines, leading to a diminished relationship between growth and moisture conditions (precipitation and PDSI). Essentially, such factors would be considered "noise" that potentially can mask or disrupt the climate "signal" in tree growth.

In summary, the pine trees we sampled may have been growing for more than two centuries, but the forest ecosystems of which they are a part have changed dramatically in the lifetime of individual trees. As one survey response notes, "How can we expect trees to behave the same way if ecosystems bear little resemblance to the places that they once were?" In GSMNP, many of the pines we sampled likely established and grew in very different conditions—soils with a moderated organic horizon, a less dense understory, with recurring fire—than what they experience now.

Not only have GSMNP forests themselves changed dramatically over the past two centuries, but the broader socioecological landscape in which they are embedded has also transformed, with implications for tree growth responses to climate. Atmospheric pollution from fossil fuel-burning power plants, mining and smelting operations, and vehicular emissions has been a particular problem in the southern Appalachians, with prevailing winds carrying pollutants to the region from throughout the Midwestern and South Central USA (Ke et al. 2007). GSMNP experiences higher levels of air pollution than any other US national park, and visibility in the park decreased 40–80% between 1948 and 2002 (National Park Service 2002). Pollutants (nitrous oxides, sulfur dioxide, carbon, and mercury) in the air are deposited by precipitation, and nitric and sulfuric acids are particularly harmful for forest ecosystems (McLaughlin and Percy 1999; Tomlinson 2003). High-elevation forests are often the most drastically and visibly impacted by acidic deposition, but pine species that characterize lower-elevation pine-oak woodlands also can be affected (Allen and Gholz 1996; Flagler and Chappelka 1996). In GSMNP, tree-ring analysis of shortleaf pines found increased trace metals and suppressed growth beginning in 1970 caused by air pollution and acidic deposition from copper smelting operations upwind (Baes and McLaughlin 1984; Shaver et al. 1994). Similar growth-trend declines have been identified in conifers elsewhere in eastern North America (Adams et al. 1985; LeBlanc et al. 1987). By altering tree growth patterns, atmospheric pollution and acidic deposition may contribute to instability in the climate-tree growth relationship over time.

Of course, understanding the histories of acidic deposition and changes in forest structure and composition does not allow us to conclusively determine one or more mechanisms for temporal instability in the growth response of pine trees to climate. We explore these factors not to develop firm conclusions but to focus on site-specific factors that are often overlooked in considerations of temporal instability. In bringing to light these possible mechanisms, we are reminded that the forests of GSMNP are products of multiple pressures that interact in complex ways. Despite the apparent absence of sustained human activity or impact, the pine-oak woodlands in GSMNP observed today are fundamentally different from the woodland ecosystems that existed when the park was created in 1934. Given such a dynamic landscape—notwithstanding variation in climate and other factors—it is not surprising that tree growth does not correspond with climatic factors in a predictable, linear fashion. While our dataset is inappropriate for climate reconstruction, it may offer an opportunity to analyze more specifically how historical changes in ecosystem structure, composition, and function influence relationships between climate and tree growth in hybrid socioecological landscapes. Additionally, instability in the response by trees to climate may provide a sense of the multiple possible trajectories that the pine-oak woodland ecosystems may take in a changing climate, thus countering the idea that the fate of an ecosystem is determined by climate and climate alone.

A Culture of Humility in Tree-Ring Science

The conceptualization of tree growth-climate relationships that we offer here is not solely our own. Many dendrochronologists are likewise grappling with the plasticity of environment-organism relationships, the limits of uniformitarianism, and the role of tree-ring science in climate change policy and politics. Not only is tree-ring science experiencing a shift in thought in which longstanding precepts are being questioned and reconfigured, but many researchers are also preaching broader changes to the culture of the field and to science in general. We conclude this chapter by reflecting on the normative implications of tree growth-climate relationships as dynamic, relational, and unstable, and explore how and why some tree-ring scientists are fostering a culture of humility in their science.

By casting doubt on tree-ring-based climate reconstructions, temporal instability also stands to threaten the authority of science and scientists in international climate change policy and "the hegemony exercised by the predictive natural sciences over contingent, imaginative, and humanistic … visions of the future" (Hulme 2011). Certainly, reconstructions may be less accurate than previously believed if trees do not respond consistently to climate over time. This realization has generated concern among researchers about climate policy that is based on climate reconstructions and models of future climate scenarios: "From my perspective, addressing the issue of temporal stability in tree-ring research is crucial to building better GCMs [global climate models]… Better models leads to better informed climate policy." Others fear that "future decisions based on 'wrong' reconstructions and false assumptions may cause harm," and note that "if we cannot trust the results from research, then we cannot have trust in the policies that are created from these results." These responses portend an ambivalence toward the "epistemological authority over the future claimed, either implicitly or explicitly, by modeling activities" (Hulme 2011).

But even as instability of growth-climate relationships might undermine hegemonic global climate policy and politics, it provides support for climate change adaptation at the local or micro-scale. Understanding responses by trees to climate as fundamentally dynamic and shaped through complex webs of interrelationships implies also that the consequences of climate change will be, as one response states, "context sensitive to the local conditions that mediate how the global change impacts the micro-environment where organisms actually live." Some researchers therefore see climate-growth research as necessary for developing management strategies that promote resilience not only for forests but also people: "Trees are so sensitive to climate changes and often are a gateway to explaining animal-climate relationships. Adaptations of trees are reflective of ecosystem changes and ultimately necessary human adaptations." In short, the plasticity of tree response to climate suggests that both human and nonhuman responses to climate change are contingent and variable rather than determined by climate alone.

While many researchers recognize the problems with policies informed by flawed scientific assumptions, they simultaneously fear that public awareness of these issues will encourage climate change denial and erode scientific authority. Responses state that "climate change deniers are always looking for ammunition and will likely use this (temporal instability)" and that tree-ring scientists should expect "further attacks from climate deniers and public officials that mistrust science." Some suggest that the only way to prevent this is to make sure claims are "absolutely waterproof," or else "the general public will lose faith in science and not care about any findings anymore." In this modernist view of science, uncertainty is viewed as "threat to collective action" and "a disease that knowledge must cure" (Jasanoff 2007, p. 33). Science must therefore be cleansed of any flawed assumptions in order to retain its privileged position as an authority on climate change.

Another position has emerged, however, among tree-ring scientists, as scientists not only interrogate long-established principles and methods but also promote broader changes in the culture of the field, embracing humility about "both the limits of scientific knowledge and about when to stop turning to science to solve problems" (Jasanoff 2007, p. 33). Our survey demonstrates that a small but vociferous subset of tree-ring scientists view temporal instability not merely as a source of uncertainty to be resolved but as a phenomenon that exemplifies the dynamic interactions among climate, landscape, trees, and people. In this perspective, temporal instability is "a positive trend," and respondents note that "perhaps there is value from understanding unstable climate relationships… Why did that happen? What caused that relationship to break down?" In addition, some researchers note that "being too definitive" is problematic in a world made of contingency and interconnection and express discomfort with the expectation that science can or should provide certainty about complex socioecological issues such as climate change. In summary, findings of temporal instability have spurred self-reflection in the tree-ring science community. This self-reflection has taken many forms. We see the most promising among them as the fostering of a culture of humility among tree-ring scientists—a culture in which researchers are "acknowledging the limits of prediction and control" and "[confronting] head-on the normative implications of our lack of perfect foresight" (Jasanoff 2003, p. 227).

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