GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 3727–3731, doi:10.1002/grl.50743, 2013

The rarity of absent growth rings in Northern Hemisphere forests outside the American Southwest

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Received 4 June 2013; revised 3 July 2013; accepted 11 July 2013; published 26 July 2013.

[1] We present a synthesis of locally absent (or "missing") growth rings across the Northern Hemisphere based on 2359 publicly available tree ring-width records. During the last millennium, widespread absent rings have been observed only in the southwestern United States and were associated with severe drought. Absent rings were uncommon during the growing seasons that followed major volcanic eruptions, including A.D. 1259 and 1816. Because these features have occurred so rarely in high-latitude and high-elevation tree ring-width records, the hypothesis that the Northern Hemisphere tree ring-width network is compromised by dating errors due to unrecognized absent rings would require that many temperature-limited forest stands in the network exhibited a reaction to cold temperatures that have essentially never been observed anywhere. If however absent-ring formation were to increase in forests outside of the American Southwest, that behavior would represent an unprecedented response to environmental stress. **Citation:** St. George, S., T. R. Ault, and M. C. A. Torbenson (2013), The rarity of absent growth rings in Northern Hemisphere forests outside the American Southwest, *Geophys. Res. Lett.*, *40*, 3727–3731, doi:10.1002/grl.50743.

1. Introduction

[2] Under environmental stress, boreal and temperate trees will occasionally form a discontinuous layer of wood about their stem, a condition described as a locally absent (or "missing") growth ring [*Glock and Pearson*, 1937; *Schulman*, 1941; *Fritts et al.*, 1965]. Absent rings occur in trees when the vascular cambium along some portion of the stem remains dormant throughout an entire growing season [*Schulman*, 1941] and are a consequence of the relatively low priority given to cambial activity when trees allocate resources [*Savidge*, 2001; *Smith*, 2008]. Studies of individual forest stands have shown that this response can be initiated by a range of environmental stressors, including moisture deficits [*Glock and Pearson*, 1937; *Fritts et al.*, 1965], fire [*Jordan*, 1966], insect outbreaks [*Swetnam and Lynch*, 1989], shading [*Lorimer et al.*, 1999], and both nearby and distant volcanic eruptions [*Biondi*, 2001; *Biondi et al.*, 2003].

Additional supporting information may be found in the online version of this article.

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0094-8276/13/10.1002/grl.50743

[3] The occurrence (or possible occurrence) of absent rings is one of the main reasons tree-ring sequences must be dated by matching relative growth patterns across many trees instead of simply counting rings [*Douglass*, 1941; *Stokes and Smiley*, 1968; *Fritts*, 1976]. Absent rings cannot be measured directly but instead are added after cross-checking the ring-width pattern from an individual ring-width series (from a single tree-ring sample) against a composite series derived from trees growing either at the same location or other locations nearby. If the ring-width pattern from an individual sample is offset from the pattern described by the composite series, that discrepancy may indicate that the growth increment for 1 year (or several) may be absent from the individual sample. Markers representing absent rings are added to ring-width measurement series if the missing ring can be identified through this cross-matching procedure (most commonly, a ring that is anomalously narrow in other tree-ring specimens will not be present in the ring-width sequence from an individual specimen) [*Stokes and Smiley*, 1968].

[4] This cross-checking procedure (known as "cross-dating") also allows each ring to be assigned an exact calendar date, which in turn facilitates the use of dendrochronology as a precise dating method for archeology [*Bayliss et al.*, 1999; *Haneca et al.*, 2009] and the earth sciences [*Jacoby et al.*, 1997; *Kitzberger et al.*, 2009] and as a source of annually or seasonally resolved information about past environmental change [*Esper et al.*, 2002; *Cook et al.*, 2004; *Osborn and Briffa*, 2006; *Cook et al.*, 2010]. Because these applications are only valid if the underlying tree-ring samples are dated correctly, the assertion that the Northern Hemisphere tree-ring network contains multiple chronological errors caused by widespread but unrecognized locally absent rings [*Mann et al.*, 2012] implicitly calls to question many findings that are based on dendrochronology and its subfields. Unfortunately, this claim has been difficult to evaluate, in part because it is not known where or when absent rings have occurred across boreal and temperate forests or what environmental factors cause the development of spatially extensive absent rings.

[5] Here we present a synthesis of locally absent rings across the Northern Hemisphere during the last millennium (A.D. 1000 to A.D. 2009) based on 2359 publicly available tree ring-width records (Figure 1a, Table S1). We demonstrate that the occurrence of absent rings varies substantially across the network, with these features occurring quite often in some regions and tree genera and very rarely in others. By showing that even the coldest years of the last millennium have not caused trees in boreal and temperate forests to form spatially extensive absent rings, we present evidence in support of the argument that disparities between climate simulations and proxy reconstructions cannot be due to dating

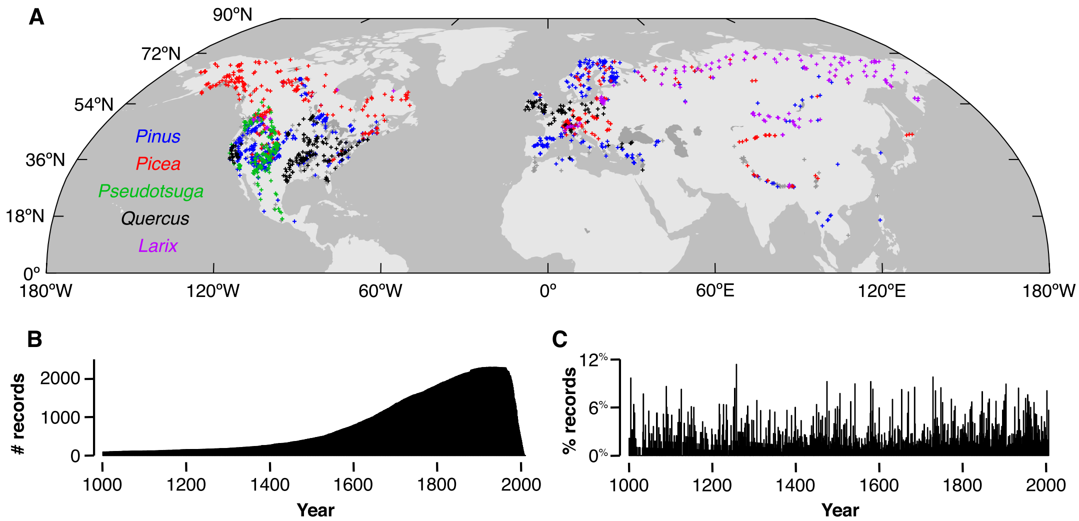

Figure 1. Northern Hemisphere tree ring-width records. (a) Map showing the location and genera of 2359 tree ring-width records across the Northern Hemisphere obtained from the International Tree-Ring Data Bank [*Grissino-Mayer and Fritts*, 1997]. The location of records derived from genera other than the five most common are indicated by grey crosses. Metadata for all records are provided in Table S1. (b) Temporal coverage of the set of ring-width records over the last millennium. (c) Percentage of tree ring-width records across the hemisphere that had one or more locally absent rings, by year.

errors in tree-ring records. We also examine the association between widespread absent rings and environmental stressors and describe a baseline for absent-ring formation across the hemisphere that could be used to evaluate future changes in forest health.

2. Northern Hemisphere Tree Ring-Width Data

[6] We obtained all tree ring-width records held by the International Tree-Ring Data Bank [*Grissino-Mayer and Fritts*, 1997] on 6 July 2012. Each record included annual time series that described ring-width measurements for one to several hundred tree-ring specimens collected at a single location. We restricted the data set to include only those ring-width records from the Northern Hemisphere with at least 10 tree-ring series. The highest concentration of records is located in the continental United States and western Europe, but the data set also has major geographic gaps, with very few records from Africa, the Middle East, India, or eastern Asia. The five most common genera used as a source for ring-width measurements are *Pinus* (850 records), *Picea* (476), *Quercus* (275), *Pseudotsuga* (205), and *Larix* (157). The temporal density of records peaked in the middle of the twentieth century and fell off gradually prior to A.D. 1900, with 442 records in A.D. 1500 and 93 in A.D. 1000 (Figure 1b).

2.1. Identifying Absent Rings

[7] The International Tree-Ring Data Bank recommends that tree-ring data submitted to the archive follow the "Tucson Decadal Format" (TDF) standard. The data bank also accepts data structured in other formats, which are subsequently converted to TDF for public release. Guidelines for TDF require ring-width measurements to represent locally absent rings with the number zero [*Holmes*, 1994;

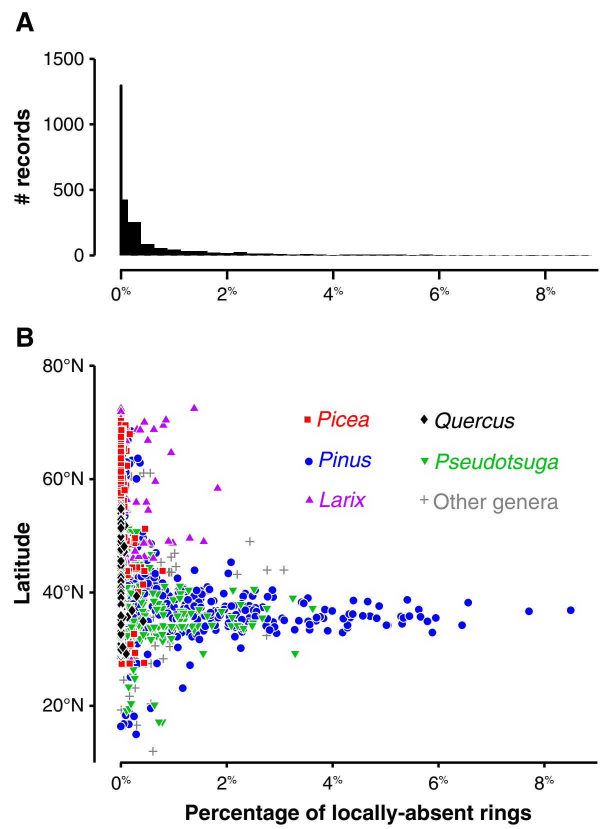

Figure 2. Frequency and distribution of locally absent rings. (a) Histogram showing the frequency of locally absent rings in tree-ring records. (b) The frequency of absent rings plotted against latitude and coded by genera.

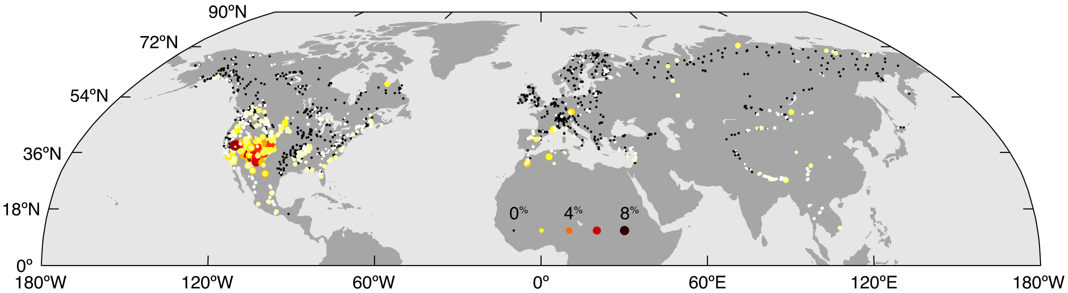

Figure 3. Map showing the percentage of locally absent rings in each record. The locations of tree-ring records that did not have any absent rings are indicated by black dots.

Grissino-Mayer, 2001]. We identified absent rings (as assigned by the original investigators) by extracting all occurrences of zero from each set of ring-width measurements that satisfied our screening criteria. For each record, we counted the number of specimens with a locally absent ring in each year, as well as the total number of specimens spanning that year.

[8] Some investigators represent locally absent rings with small nonzero values [*Büntgen et al.*, 2005], but information about this practice is not included in metadata associated with ring-width measurements. As a result, our approach could miss absent rings that occurred in individual tree-ring specimens but were recorded using a notation that does not comply with the TDF standard. To address this possibility, we repeated our analysis using a more relaxed criteria where both zero values and measurements of 0.001 mm (the smallest nonzero measurement allowed in TDF data) were assumed to represent absent rings. Using this more liberal standard ensures that all absent rings, regardless of the notation used to represent them, are identified as absent rings, but it will also misclassify a number of narrow (but present) rings as absent. Adopting this alternative criteria did not produce any substantive differences in our final results, including the frequency of absent rings across geographic regions and genera and their occurrence following major volcanic eruptions.

3. Absent Rings in Boreal and Temperate Trees

[9] During the last millennium, the percentage of ring-width records that contained at least one absent ring for a given year ranged between 0 and 11.3% (Figure 1c). Over the entire data set, on average, one locally absent ring was observed for every 240 rings that were present. More than half of all records (1296 of 2359) did not contain a single absent ring (Figure 2a). The frequency of absent rings (expressed as a percentage of the total number of rings within each record) varied substantially by genera and

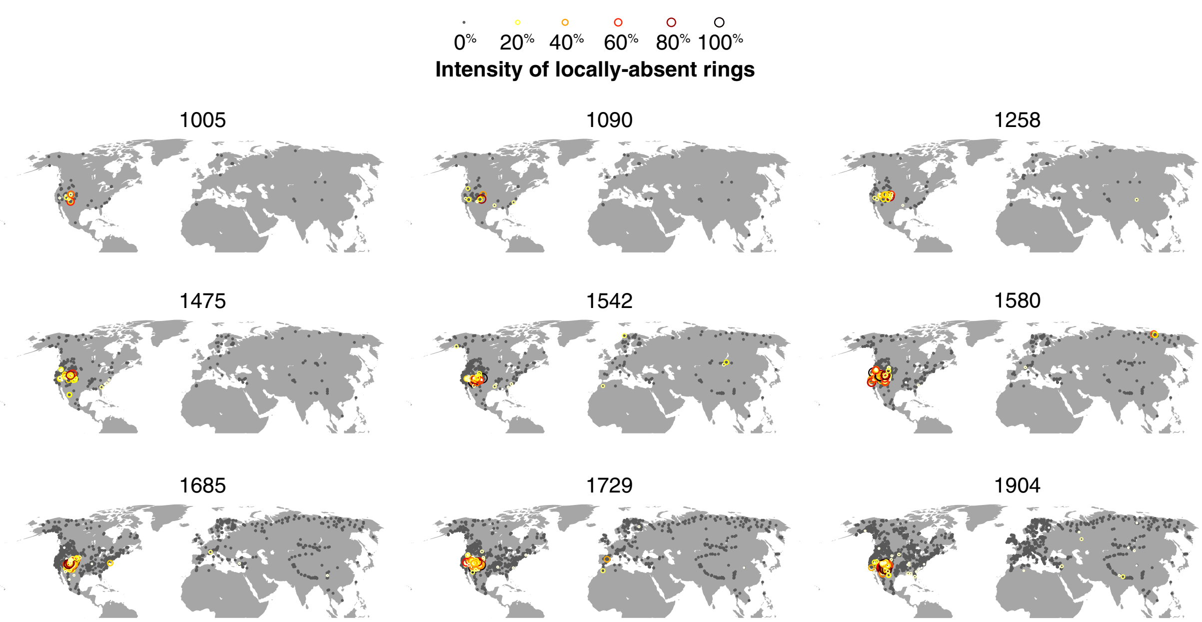

Figure 4. Years during the last millennium when absent rings were most widespread. Each map shows the intensity of locally absent rings (the percentage of tree-ring specimens that contain an absent ring for a given year) when these features were most frequent at sites across the Northern Hemisphere. The locations of records that spanned each year but did not have any absent rings are indicated by grey dots.

latitude (Figure 2b). Absent rings were most common in *Pinus* (0.8% of all rings are absent) and *Pseudotsuga* (0.6%), particularly within records located between 30°N and 40°N. They formed occasionally in *Larix* (0.2%) and were very rare in *Picea* (0.03%) and *Quercus* (0.01%). Mapping the same metric (Figure 3) showed that records with a very high frequency of absent rings (more than 2% of all rings being absent) were found only within the region centered over the southwestern United States. Absent rings were extremely uncommon at high latitudes; poleward of 50°N, the absent : present ratio increased from 1:240 to 1:2500. Although the frequency of absent rings is reported only rarely in published studies using dendrochronology, our results are broadly consistent with the occurrence of these features in ring-width records at sites across the Northern Hemisphere (Table S2).

[10] We defined the intensity of locally absent rings as the percentage of tree-ring specimens within a single record that contain an absent ring for a given year and mapped that parameter to identify spatial patterns in the occurrence and frequency of absent rings. Widespread absent rings (cases where a high percentage of the Northern Hemisphere network formed at least one absent ring) (Figure 1c) were observed only in the southwestern United States (Figure 4, Figure S1). To a degree, this result is a by-product of the high number of tree-ring records developed within this region during the last century [*Nash*, 1999], but it also reflects the fact that absent rings have formed more often in the southwestern United States than anywhere else in the hemisphere (Figure 3). In all cases when widespread absent rings occurred in the American Southwest, those events coincided with severe droughts over the same area as estimated from moisture-sensitive tree-ring records [*Cook et al.*, 2004] (including many of the same records used in this study), which confirms that these features are most commonly an extreme manifestation of the drought response exhibited by trees growing in semiarid environments [*Fritts et al.*, 1965; *Fritts*, 1976]. Absent rings were neither intense nor widespread during the growing seasons that followed the four largest stratospheric sulfate aerosol injection events of the last millennium [*Gao et al.*, 2008], including A.D. 1259 and the "Year Without a Summer" in A.D. 1816 (Figure S2) or during the coldest year in the Northern Hemisphere in the last 1500 years (A.D. 1644) [*Mann et al.*, 2009] (Figure S3). Based on these results, we conclude that severe drought has been the primary cause of widespread absent rings across the Northern Hemisphere during the last millennium. There is no evidence that low growing-season temperatures and other stressors have been able to force the same response at similar spatial scales.

4. Concluding Remarks

[11] Dendrochronological theory [*Fritts*, 1976], ecological field observations [*Körner and Paulsen*, 2004], and physiological modeling [*Boisvenue and Running*, 2006] indicate that temperature during the growing season is the principal limit to tree growth near arctic and alpine treeline, and paleotemperature estimates from tree rings [*Esper et al.*, 2002; *Osborn and Briffa*, 2006] have been most often based on samples obtained from these ecotones. Recently, *Mann et al.* [2012] argued that discrepancies between climate model simulations and dendroclimatic reconstructions were due to unrecognized absent rings and resulting chronological errors. This scenario is not consistent with the pattern of absent-ring formation outlined by more than 17 million tree rings. Locally absent rings are extremely rare in tree-ring records from high latitudes (Figure 2b, Figure 3) and high elevations (Figure S4). They are also rare or uncommon in the two genera (*Picea* and *Larix*) that dominate this part of the network (Figure 2b, Figure S5). The set of 476 *Picea* records collectively spanned 134,881 "tree-ring years", but there were no cases where the growth ring for a given year was absent from every tree at the same site (a "completely absent" ring). Even the individual *Picea* record with the highest percentage of absent rings for that genera (chin034, Figure S5) did not have more than 30% of tree-ring series showing an absent ring in any single year. Over 157 *Larix* records, there were only two cases of a completely absent ring: A.D. 1715 at Dayan Nuur, Mongolia and A.D. 1718 at Crater Mountain, Washington (and during this year, this record was based on data from only one tree). The hypothesis that the Northern Hemisphere tree ring-width network is compromised by dating errors due to unrecognized absent rings would require all of the trees (without exception) that contribute to many (or most) *Picea* and *Larix* records to have formed an absent ring during the same year and to have done so repeatedly over the last millennium. Because our analysis has shown that *Picea* and *Larix* form absent rings only very rarely, this scenario would require many temperature-limited forest stands in the Northern Hemisphere to have exhibited a reaction to thermal stress that has essentially never been observed at any individual site. We argue this style of response is unlikely and suggest that the apparent differences between simulations and proxies cannot be attributed to dating errors in tree-ring records.

[12] Ecological studies conducted in northern Arizona nearly 50 years ago [*Fritts et al.*, 1965] established that locally absent rings occur most frequently at semiarid sites close to the lower forest border, where trees are slow growing and ring-width is highly variable over time. Conversely, absent rings are less common in trees from the forest interior, where growth rates are higher and ring-width series exhibits less variability. Our analysis indicates this framework also holds at much larger spatial scales. Over the Northern Hemisphere, absent rings are most common in trees at sites where growth is limited by moisture availability but where tree growth is not primarily limited by moisture, ring-width series contain very few or no locally absent rings. These observations also set a baseline that could be used to evaluate future changes in forest health. Recent warming may have caused boreal forest trees to become more sensitive to drought stress [*Barber et al.*, 2000], but it has been difficult to determine if this shift should be attributed to natural climate variability or global climate change [*Allen et al.*, 2010]. Because absent rings have occurred so rarely outside of the southwestern United States, future increases in their rate of formation at other locations would indicate that forests are exhibiting a response to environmental stress that is without precedent during at least the last millennium.

[13] **Acknowledgments.** S.S. acknowledges support from the University of Minnesota's Institute on the Environment. We thank K. Anchukaitis, D. Griffin, M. Hughes, A. Macalady, and two anonymous referees for comments and discussion, and B. Bauer for technical assistance.

[14] The Editor thanks Markus Stoffel and an anonymous reviewer for their assistance in evaluating this paper.

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