Dendrochronological responses to the 24 October 1992 tornado at Sunset Crater, northern Arizona

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Abstract: This paper documents tree-ring responses to a historic tornado and reevaluates prehistoric tree-ring changes seen in archaeological wood of Wupatki Ruin used to date the 11th-century eruption of Sunset Crater. The historic tornado occurred at Sunset Crater, northern Arizona, on 24 October 1992, and trees within areas damaged by the tornado survived the event and continue living today. The objectives of this research were to document their ring-growth changes and to consider the possibility of tornadoes as a candidate disturbance for the prehistoric ring-growth changes of Wupatki. About half of the trees sampled within areas damaged by the tornado show one or more dendrochronological responses to that event, including ring-width release, reaction wood, ring-width suppression, and (or) reduced latewood. Tornado damage is not a likely candidate for having caused the abrupt ring-width changes at AD 1064–1065 seen at Wupatki. However, five living ponderosa pines (*Pinus ponderosa* Dougl. ex P. & C. Laws.) at Sunset Crater experienced abrupt and severe suppressions in ring growth beginning decades ago and continuing today. No single disturbance seems obvious for causing these growth suppressions, but further research is merited to find the cause of these modern suppressions to propose a new candidate explanation for the AD 1064 suppression.

Résumé : Cet article décrit la réaction des cernes annuels de croissance à une tornade passée et réévalue les changements observés dans les cernes préhistoriques du bois archéologique de Wupatki Ruin qui a été utilisé pour dater les éruptions du Sunset Crater survenus au 11^{e} siècle. La tornade passée est survenue à Sunset Crater, dans le nord de l'Arizona, le 24 octobre 1992 et des arbres dans la région affectée par la tornade ont survécu et sont toujours vivants aujourd'hui. Les objectifs de cette recherche consistaient à décrire les variations de leur croissance annuelle et à examiner la possibilité qu'une tornade soit la perturbation responsable des variations dans les cernes annuels préhistoriques de Wupatki. Environ la moitié des arbres échantillonnés dans la région touchée par la tornade montrent une ou deux réactions dendrochronologiques à cet événement incluant : des cernes plus larges, du bois de réaction, des cernes plus minces ou moins de bois final. Il y a peu de chances que des dommages dus à une tornade aient causé les changements abrupts dans les cernes observés en 1064 et 1065 apr. J.-C. à Wupatki. Cependant, cinq pins ponderosa (*Pinus ponderosa* Dougl. ex P. & C. Laws.) vivants à Sunset Crater ont subi il y a plusieurs dizaines d'années une diminution abrupte et sévère de croissance qui se poursuit aujourd'hui. Aucune perturbation en particulier ne semble être la cause évidente de cette réduction de croissance mais cette situation mérite qu'on continue les recherches pour trouver la cause de ces réductions récentes de croissance dans le but de proposer une nouvelle explication pour la réduction de croissance détectée en 1064 apr. J.-C.

[Traduit par la Rédaction]

Introduction

This paper documents tree-ring responses to a historic tornado and reevaluates prehistoric tree-ring responses used to date the 11th-century eruption of Sunset Crater. Past dendrochronological research on tree-ring responses to wind has focused on persistent, long-term wind regimes and has shown reaction-wood responses along axes parallel to predominant wind directions (Robertson 1986, 1991; Wade and Hewson 1979). Other forest ecological research has shown long-term changes in forest species composition and stand structure due to tornadoes (Glitzenstein and Harcombe 1988; Peterson 2000*a*; Harrington and Bluhm 2001). However, little research has been published showing tree-ring responses to tornadoes, that is, long-term growth changes due to short-term, intense winds.

The tornado of interest occurred at Sunset Crater, northern Arizona (Figs. 1*a*, 1*b*), at 1430 on 24 October 1992 (Arizona Daily Sun Staff 1992). The tornado first touched ground south of Sunset Crater and then moved north by northwest towards O'Leary Peak (Fig. 1*c*) before dissipating. Many trees were uprooted and killed by the intense winds of the tornado, but other trees growing within the swaths damaged by the tornado survived the event and continue living today, now 13 years later.

Given that the dating of this tornado is historically well documented (Arizona Storms Database; http://ag2.calsnet.

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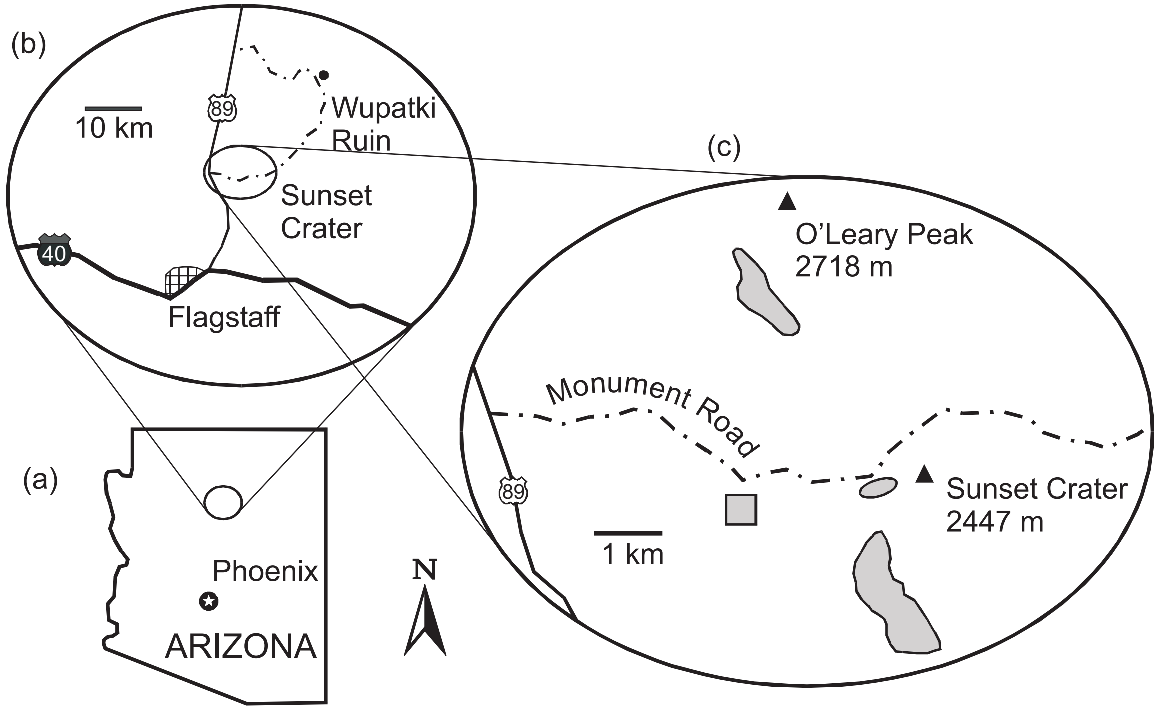
Fig. 1. Site maps. (*a*) The state of Arizona, (*b*) regional detail north of Flagstaff, and (*c*) site detail near Sunset Crater. Filled irregular polygons denote the tornado swath areas, and the filled square is the subsite where control trees were located.



arizona.edu/cgi-bin/storms.cgi), it can serve as a test case for dendrochronologically calibrating ring-growth changes in trees that were buffeted, but not killed, by high winds. Enough time has passed since the 1992 tornado at Sunset Crater to assess its impact on ring growth of trees that survived it, so the primary objective of this research was to document those ring-growth changes. Such a calibration could serve to identify tornadoes of the past.

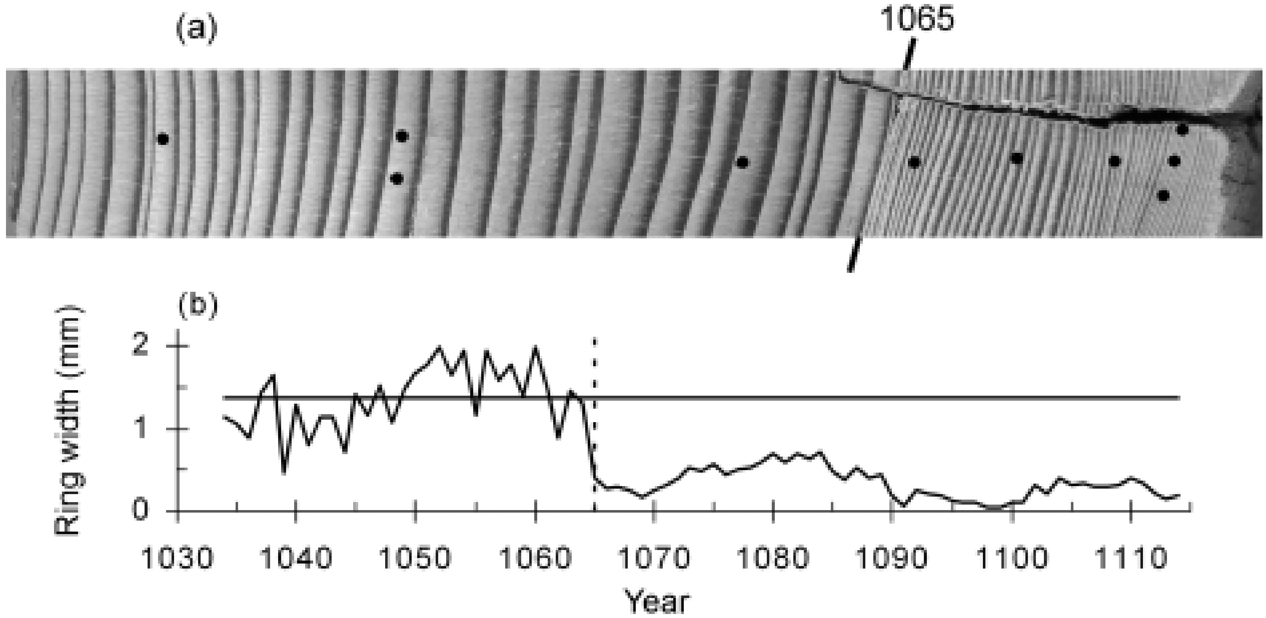
This calibration could also establish tornadoes as a candidate disturbance in tree-ring samples showing changes in prehistoric ring growth. An additional goal of this research is to reevaluate the cause of long-term ring-growth changes in prehistoric wood samples recovered from the nearby Wupatki Ruin, situated 20 km northeast of Sunset Crater (Fig. 1*b*). Two ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) and one Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) roof beams recovered from this site show abrupt reductions in both absolute ring width and in relative interannual variability beginning with the AD 1065 ring (Fig. 2). These ring-growth changes have been interpreted as evidence of, and dating for, the eruption of Sunset Crater in AD 1064 (Smiley 1958), which has been a highly significant date in both geological and archaeological research in the United States Southwest (Colton 1960; Pilles 1979, 1987; Holm and Moore 1987; Downum 1988; Duffield 1997). However, recently this date has been questioned (Boston 1995; Elson et al. 2002; Elson and Ort 2003), in part because the number of tree-ring samples is small and the provenance of the analyzed trees is not known. Wupatki, at an elevation of only 1495 m a.s.l., is too hot and dry to support the growth of pine and fir, both today and in the prehistoric past (Sullivan and Downum 1991, p. 272); presently, the closest that these species are found relative to Wupatki is 10–20 km for ponderosa pine and 20–30 km for Douglas-fir, to the southwest for both species. Therefore, these trees could have come from anywhere in the higher elevations of the area, possibly from sites not heavily affected by ash and cinder fall from the eruption of Sunset Crater. Additionally, while reductions in ring width and interannual variability could have been caused by volcanism, ring-growth changes like these can also be caused by other events of an ecological (e.g., Fritts and Swetnam 1989), geological (e.g., Jacoby 2000), or even ethnobotanical (e.g., Swetnam 1984) nature.

Tornadoes have not been considered as a candidate explanation for the 1064 event because they are not common at high elevation (Ahrens 1988) and more specifically the 1992 tornado is the only known historical event of its kind in the Flagstaff area (Crisp 1996). Therefore, no historic tornado had ever occurred in the Flagstaff area by 1958, the year of publication of the AD 1064 date for Sunset Crater. The secondary objective of this research was to consider the possibility of tornadoes as a candidate disturbance for the ring-growth changes of the Wupatki specimens.

Methods

The study area is located about 25 km northeast of Flagstaff, Arizona (Fig. 1*b*), at an elevation of about 2200 m a.s.l. The climate is cool and dry, as typified by the meteorological record of Sunset Crater National Monument (monthly data from 1970 to 2004 obtained online from the National Climatic Data Center; http://www.ncdc.noaa.gov/oa/ncdc.html), which has a mean annual temperature and precipitation of 8 °C and 432 mm, respectively. Soils are Typic Ustorthents, or weakly developed, deep, coarse, excessively drained cinders (Miller et al. 1992) with a thin layer of pine needles as

Fig. 2. Evidence for environmental change in the Sunset Crater area at AD 1064–1065. (*a*) A beam sample from Wupatki (catalog No. WPT12) showing an abrupt change in ring growth beginning in AD 1065 and (*b*) its ring-width series with a fit line. The fit line of the ring-width series is the average width of rings up to and including AD 1064, which was extrapolated through the rest of the series. Dots on the sample indicate decadal years, with the double dots indicating AD 1050 and triple dots indicating AD 1100. The broken line indicates AD 1065.



the surface organic matter. Forest vegetation is primarily ponderosa pine with some quaking aspen (*Populus tremuloides* Michx.). Based on tree counts from a 1997 aerial photo, stand density in the area of Sunset Crater averages 63 ± 18.2 trees·ha^{-1} (mean ± SD, n = 10 one-hectare plots), which converts to an average nearest-neighbor distance of 14 m.

Field sampling was done in the summer and fall of 2004, or about 12 years after the tornado. Living trees in three areas damaged by the tornado (Fig. 1*c*) were increment cored to obtain their tree-ring records. Additionally, trees from a separate site 2 km west of the tornado swaths (Fig. 1*c*) were sampled to serve as control specimens for comparison. All trees sampled were ponderosa pine and all were living in 1992 as well as at the time of this fieldwork. Sampled trees averaged 20 cm in diameter and ranged from 5 to 10 m in height.

Field procedures followed typical methods of dendrochronology (Phipps 1985). Trees were selected based on their extent of damage by the tornado: some had crowns damaged or broken, others were completely knocked over but still living, and others showed no apparent damage. Trees were cored using 5.1 mm diameter borers. At least one radius was collected per tree, but occasionally more radii were collected to determine ring-growth patterns all around the trunk (Sheppard and Jacoby 1989). No effort was made to collect radii along specific sides of the trees, effectively randomizing the aspects of samples.

Laboratory treatment of the samples also followed typical methods of dendrochronology (Swetnam et al. 1985). Cores were air dried, glued into protective sticks to display a transverse surface, and then sanded to enhance the visibility of the rings (Yamaguchi and Brunstein 1991). Samples were visually cross-dated by matching patterns of wide and narrow rings across trees (Douglass 1941), and then the widths of dated rings were measured to ±0.01 mm (Robinson and Evans 1980).

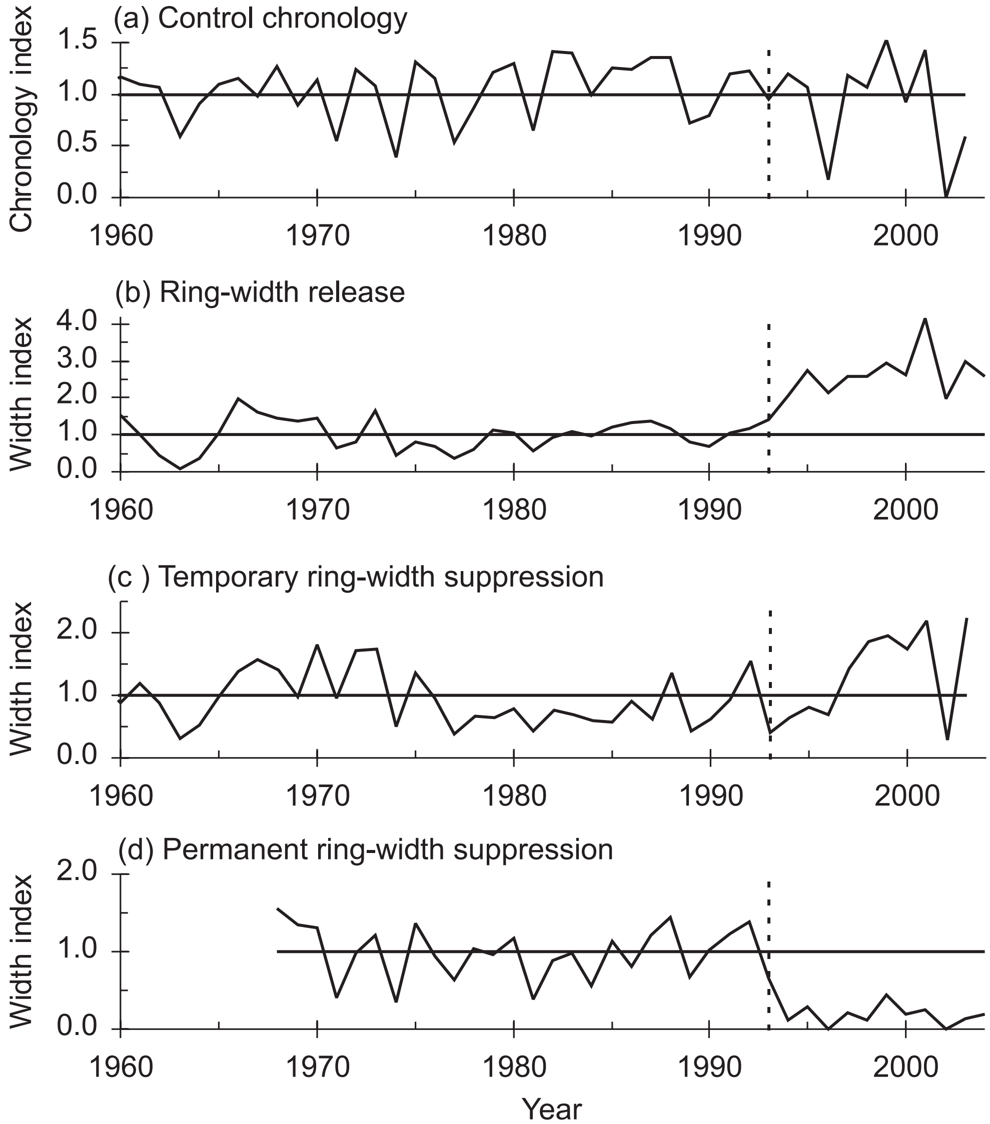
Analytical reduction of the data mostly followed standard procedures. Accuracy of dating and measurement was checked by cross-correlation analysis (Program COFECHA, Holmes 1983; Grissino-Mayer 2001). Dating accuracy was also verified by cross-correlation with preexisting ponderosa pine chronologies developed independently by others for the same general area (Grissino-Mayer and Fritts 1997).

Ring-width index series were developed in different ways depending on whether the trees were affected by the tornado. For control trees sampled outside the tornado swaths, ring-width series were detrended using all rings from pith to 2004. For trees within the tornado swaths and that showed ring-growth changes beginning in 1993 or later, ring-growth series were detrended using only the rings from pith to 1992. These fit lines were then extrapolated to 2004 (Mutch and Swetnam 1995; Sheppard and White 1995). In all cases, index values were calculated as ratios of observed widths divided by predicted widths (Fritts 1976). For the control chronology of trees growing outside the tornado swaths, the resultant index series were averaged into a site chronology using the arithmetic mean (Cook 1985). To demonstrate and quantify ring-growth responses to the tornado, index values were compared both pre- and post-event in trees affected by the tornado as well as between affected and nonaffected trees.

Results

Trees sampled outside the tornado swaths cross-date quite strongly. Among themselves, their average correlation with their chronology is r = 0.77, and their site chronology correlates strongly with preexisting ponderosa pine chronologies from nearby. Since 1992, only 1996 and 2002 were well below average (Fig. 3*a*), in both cases because of winter rainfall preceding those growing seasons that was also well below-average. In-

Fig. 3. Time series of Sunset Crater ring-width growth related to the 1992 tornado. (*a*) Control chronology composed of ponderosa pine located well away from tornado swaths, (*b*) ring-width release of sample in Fig. 4*a*, (*c*) temporary ring-width suppression of sample in Fig. 4*d*, (*d*) permanent ring-width suppression of sample in Fig. 4*e*. The broken lines indicate 1993.



deed, the winter preceding the 2002 growing season (October through April) was the driest on record for Sunset Crater National Monument, and none of the control trees grew a ring for that year, resulting in an index value of zero for 2002.

Tree-ring responses to the October 1992 tornado

Eighty-three living trees were sampled within the tornado swaths, 47 of which (57%) show one or more dendrochronological responses to the 1992 tornado. These event-response trees were mostly young and (or) small, averaging 60 years in age and 17 cm in diameter. Young and (or) small trees apparently were able to withstand the high winds without losing substantial amounts of crown or being fully uprooted, confirming other research showing that older, larger trees are more susceptible to being killed by high winds (Peterson 2000*b*).

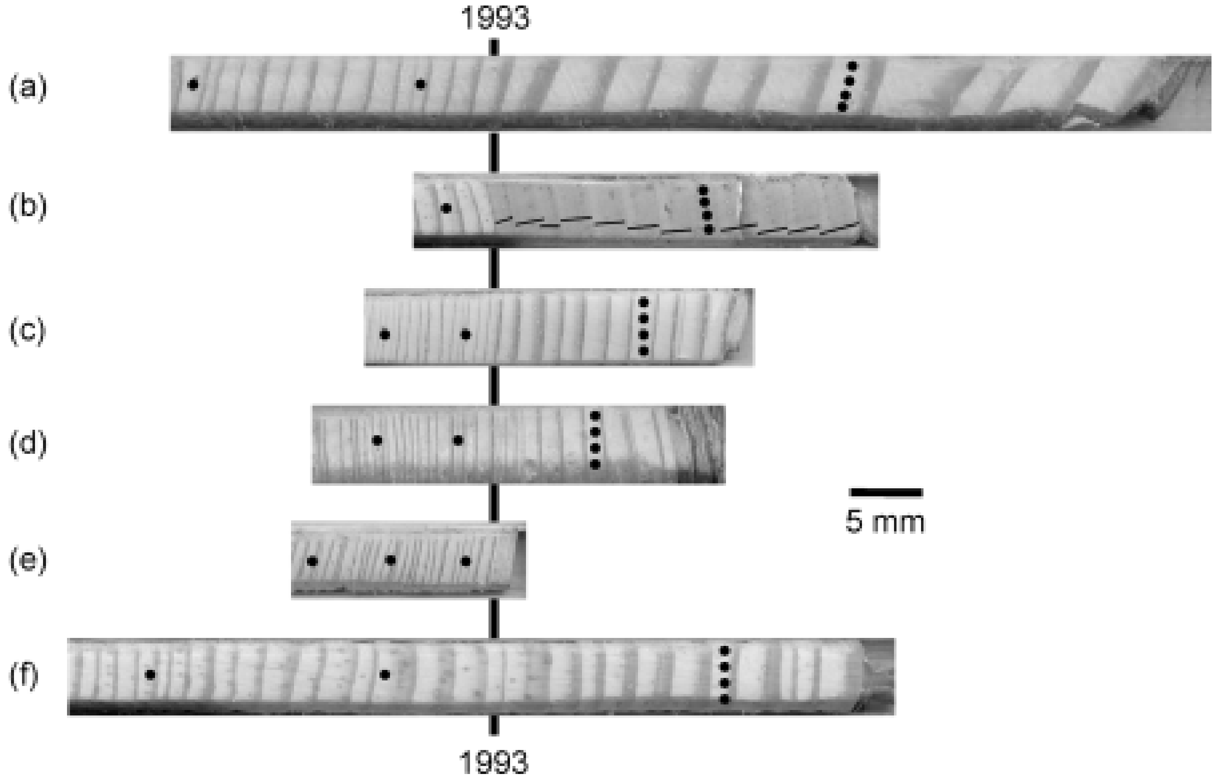
Growth release

Fifty-seven percent of response trees show a release in radial growth (wider rings) beginning with 1993 and continuing even now, 12 years after the tornado (Fig. 4*a*). These wide rings are composed of normal tracheids, as opposed to radially elongated tracheids, for example. The post-tornado ring-growth rate has been about twice that of the 10 rings immediately prior to the tornado, and the ring-width index series of these trees show an abrupt positive departure from expected growth beginning in 1993 (Fig. 3*b*). This growth release is quite different from the control chronology for the same time period (Fig. 3*a*).

Reaction wood

Twenty-eight percent of response trees show reaction wood in the form of discolored tissue beginning with 1993 and continuing even now. Half of these trees show reaction wood for the full rings (Fig. 4*b*), while the other half show reaction wood only in the latewood portions and (or) for only the first couple of rings after the tornado (Fig. 4*c*). Perhaps the trees with partial reaction wood were not buffeted as much and they returned to normal growth more quickly. Many reaction-

Fig. 4. Examples of Sunset Crater ring-width responses to the 1992 tornado. (*a*) Increasing ring widths, (*b*) classic reaction (compression) wood for entire rings, (*c*) reaction (compression) wood evident only in the latewood portions of each ring, (*d*) temporary ring-width suppression followed by a return to normal growth, (*e*) permanent ring-width suppression, (*f*) thin latewood width relative to total ring width. Dots on the sample indicate decadal years, with the quadruple dots indicating AD 2000.



wood rings are also abnormally wide, which is generally common for reaction wood (Douglass 1940*b*). Some of these trees were tilted but not uprooted, and reaction-wood responses occurred primarily on the bottom of the now-horizontal trees, less so on the sides or top.

Suppressed growth

Six percent of response trees show some varying degree of suppressed growth after the tornado. One of these trees has just four unusually narrow rings, from 1993 to 1996, as compared to growth of the control chronology (Figs. 3*c* and 4*d*). Another tree shows highly suppressed ring growth ever since 1993 (Figs. 3*d* and 4*e*).

Reduced latewood

Forty-five percent of response trees show an unusually thin latewood band for just the 1993 ring (Fig. 4*f*). Considering the 6-year period from 1990 to 1995, latewood averaged 22% of total ring width in control trees, with 1993 being no different from neighboring rings (Fig. 5*a*). By contrast, latewood averaged only 10% of the 1993 ring in event-response trees (Fig. 5*b*). The total width of the 1993 ring in these event-response trees was also typically below average, though not as dramatically as for latewood width.

Long-term ring-width suppression

Another tree-ring growth anomaly not related to the 1992 tornado was observed during this research. Five living ponderosa pines show abrupt and severe suppressions in ring growth beginning decades ago and continuing today. These long-term growth suppressions did not start synchronously across trees. As an example, one of these pines switched from a mode of normal ring growth to one of highly suppressed growth beginning in 1930 (Fig. 6*a*). Ring growth since 1930 does not cross-date, but the average growth rate since 1930 (0.11 mm·year^{-1}) was much lower than previous growth rates as well as lower than growth predicted for post-1930 (Fig. 6*b*).

Discussion

Tree-ring responses to tornado

Ring-width release due to the October 1992 tornado near Sunset Crater could have been caused by either or both of two mechanisms. First, because the tornado uprooted and killed many trees (Crisp 1996), the surviving trees are now living in microsites with less intertree competition for light and (or) soil resources than before. For example, based on tree counts from a 1997 aerial photo, stand density within the southernmost tornado swath averages 18 ± 7.0 trees·ha^{-1} (n = 10 one-hectare plots), which converts to an average nearest-neighbor distance of 27 m. This is significantly different ($p < 0.001$, two-tail t test) than the 63 trees·ha^{-1} found around Sunset Crater generally.

A logical tree-growth response to reduced competition could be increased growth by survivors, similar to how selective thinning of stands can enhance growth of the remaining trees during intensive forest management (Ffolliott et al. 2000). However, a drawback to this rationale is that the ponderosa pine forest around Sunset Crater was already sparse. As a

Fig. 5. Time series of Sunset Crater percent latewood width relative to total ring width related to the 1992 tornado. (*a*) Control chronology composed of ponderosa pines located well away from the tornado swaths and (*b*) reduced percent latewood for 1993. The broken lines indicate 1993.

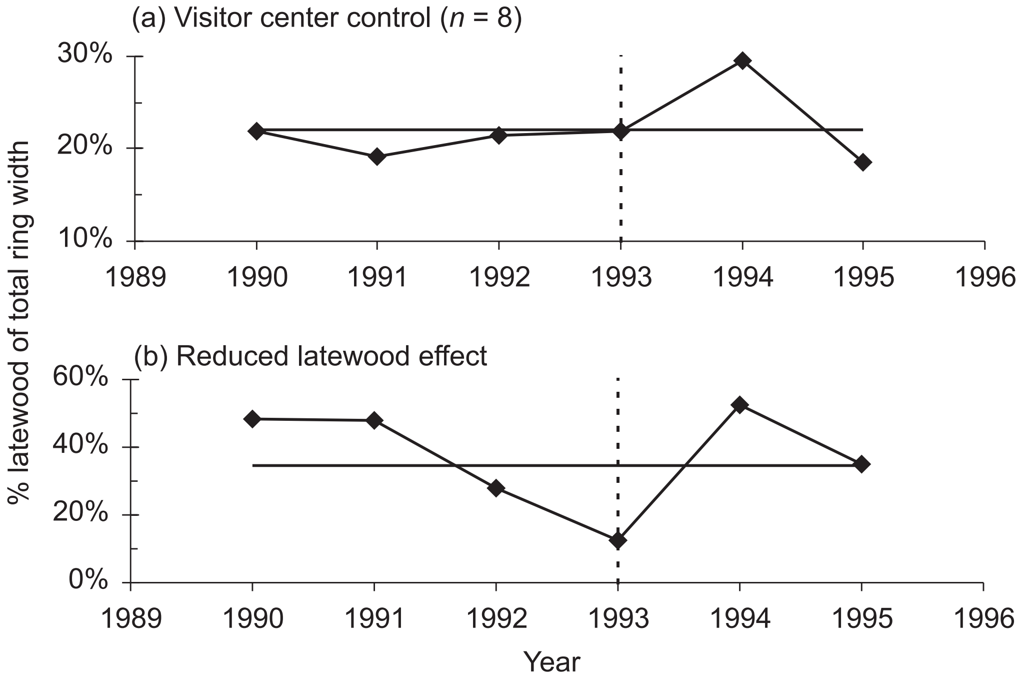
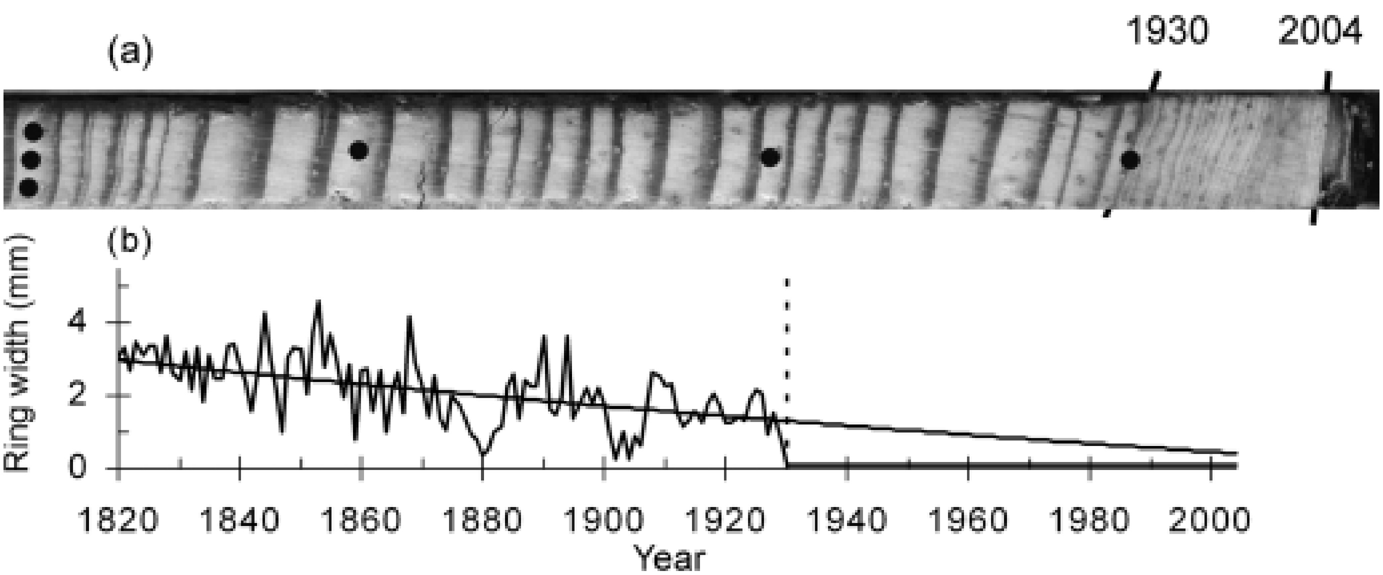


Fig. 6. Very long-term suppression of radial tree growth. Ring growth on this still-living tree abruptly slowed down beginning in 1930 and has yet to recover. Dots on the sample indicate decadal years, with the triple dots indicating the AD 1900 year. The broken line indicates 1930.



reference comparison, the average stand density within a ponderosa pine forest located 40 km south of Flagstaff was 1900 trees·ha^{-1} (Covington and Moore 1994), which converts to an average nearest-neighbor distance of 2.6 m, much denser than the forest around Sunset Crater. Irrespective of tornado disturbance, intertree competition has probably not been an important limiting factor for tree growth at Sunset Crater.

Second, the increased radial growth since 1993 might be an example of thigmomorphogenesis, that is, a physiomorphological response to a short-term perturbation such as high winds (Jaffe and Forbes 1993). Radial growth increases have been shown for various tree species due to mechanical treatments that mimic the intense buffeting of trees that occurs during a tornado (Telewski and Jaffe 1981, 1986*a*, 1986*b*; Valinger et al. 1995; Telewski and Pruyn 1998; Pruyn et al. 2000). This ring-growth response does not necessarily involve greatly altered tracheids, but instead appears to be due to creating more tracheids than normal (Telewski 1989). Affected trees are not necessarily tilted permanently by these short-term perturbations, and the ring-width release might involve a hormonal mechanism as opposed to being a gravitropic response (Takahashi and Jaffe 1984; Telewski and Jaffe 1986*c*).

Reaction wood has been defined as tissues formed by leaning trees in response to changed gravitational stress (Dadswell and Wardrop 1949). Compression wood, the version of reaction wood that occurs in conifers, is readily distinguishable by a darker, often orangish color of the rings, the round shape and thick walls of the tracheids (Van der Sijde et al. 1985), and the lack of a sharp demarcation between earlywood and latewood portions within a ring (Dadswell and Wardrop 1949). All these characteristics are evident in the reaction-wood specimens of Sunset Crater. Chemically, reaction wood is typically high in lignin (Baillères et al. 1997), which might be at least part of the cause of the distinguishable color of the wood (Kwon et al. 2001). Compression wood has been used to dendrochronologically date forest disturbances (including wind) that have tilted trees (Pillow 1931; Akachuku 1991; Wimmer 2002).

Reaction wood is a common response to tilting of a tree (Scurfield 1973; Kwon et al. 2001), and the amount of lean needed to prompt a tree into forming reaction wood can be as little as just 2° off vertical (Timell 1986, p. 1156). However, compression wood has been found in trees with no lean whatsoever (Timell 1986, p. 1132), and the phenomenon of spiral compression wood, where the compression tracheids exist all around a tree stem but in different growth rings (Douglass 1940*a*; Telewski 1988) also illustrates how compression wood is not necessarily always a response to unidirectional lean. Although a few of the tornado survivors are leaning, some all the way to horizontal, most of the trees at Sunset Crater are not leaning discernibly. While reaction wood can be caused by other disturbances, compression wood was an obvious dendrochronological response to the 1992 tornado and can be a conclusive indicator of tornado when seen in conjunction with other ring-growth responses.

Ring-growth suppression can occur as the result of various disturbances that reduce tree uptake of soil moisture and (or) photosynthesis (Shroder 1980). Although ring-growth suppression was not the dominant response to the 1992 tornado, it can help indicate tornadoes when seen in conjunction with other ring-growth responses.

Reduced latewood growth in conifers has been associated with partial defoliation of trees. Latewood development is often more sensitive to defoliation than total ring width (Krause and Morin 1995). For example, defoliation by sawfly and budworm has altered the structure and anatomy of latewood bands in fir, spruces, and pine (Filion and Cournoyer 1995; Gross 1992; Jardon et al. 1994). Similarly, the June 1908 explosion in Tunguska, Siberia, altered latewood morphology in spruce and larch (Vaganov et al. 2004); one effect of that explosion was thought to be partial defoliation, perhaps due to excessive exposure to the heat of the explosion. Interestingly, the response of altered latewood to defoliation often lasts for only one ring, a pattern that was shown by many Sunset Crater pines.

Based on eyewitness accounts, the Sunset Crater tornado did not result in noticeable defoliation per se in surviving trees (personal communication, US Forest Service workers who managed the clean up after the tornado, 2005). However, experimentation with winds of 11 $m \cdot s^{-1}$ resulted in significantly damaged needles due to surface abrasion, either from airborne particulate impaction or from the needles violently rubbing against each other (Van Gardingen et al. 1991). Given that tornado winds peak out at speeds much higher than 11 $m \cdot s^{-1}$, and given that the ground surface at Sunset Crater is composed of light, rough-textured cinders, it could have been that needles were damaged on pines that show thin latewood in 1993. Such wind damage might have effectively simulated defoliation without actually defoliating the trees. By this reasoning, reduced latewood width can be a conclusive indicator of a tornado.

Decades-long suppression in pine

The decades-long suppression observed in five sampled pines is pertinent to the general investigation of Sunset Crater. These very long-term suppressions closely resemble the dendrochronological changes that were used to establish AD 1064 as the date of the eruption (Smiley 1958). No eruption occurred at the time of these 20th-century abrupt changes, and the task remains to determine what caused these suppressions, as that disturbance might become a candidate for explaining the tree-ring changes at AD 1064. We have not observed any unusual geomorphological characteristics about these trees that might have caused their suppression, and at this point no single disturbance is obvious for causing the abrupt, long-term suppressions of ring growth at Sunset Crater. Some options include the following:

(1) Earthquakes have caused very long-term suppressions for still-living trees that were physically damaged but not killed (Jacoby et al. 1988). However, those cases involved substantial loss of crown and (or) perhaps severing of roots. The Sunset Crater trees do not show such severe external damage, and the onset dates of suppression at Sunset Crater do not correspond to any known, large earthquake in the vicinity.

(2) Root fungi have slowly reduced ring growth for decades before the affected trees finally die (Cherubini et al. 2002). However, the Sunset Crater suppressions were abrupt and therefore do not exactly match the root fungus example.

(3) Regional, non-point-source pollution can cause lengthy, wide-spread reductions in tree-ring growth (Graybill and Rose 1989; Grissino-Mayer and Fritts 1995). However, most of the long-term suppressions at Sunset crater predate putative pollution influxes to the area, and long-term suppression at Sunset Crater is not wide spread as only five sampled trees show it.

(4) Diffuse emission of magmatic CO_2 has affected tree growth (Cook et al. 2001), but that disturbance ultimately killed the affected trees (Farrar et al. 1995). Consequently, this response did not last for several decades. Furthermore, Sunset Crater trees with the decades-long suppression are growing close to trees without any suppression, and magmatic CO_2 presumably would have affected whole pockets or stands of trees.

Conclusions

The October 1992 tornado damaged trees in the Sunset Crater area, northern Arizona, and resulted in multiple tree-ring responses in surviving trees. Taken together, these multiple dendrochronological signals can be used to date and study past tornadoes. However, reduced ring widths and low interannual variability were neither the dominant nor even the most common response to the 1992 tornado at Sunset Crater, and thus tornado damage is not a likely candidate for having caused the abrupt changes seen at AD 1064–1065 from the Wupatki beams, whose exact geographical origin remains unknown.

Acknowledgments

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