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*Letter to the editor*

# Fire histories in ponderosa pine forests of Grand Canyon are well supported: reply to Baker

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*Abstract.* Fire scars and other paleoecological methods are imperfect proxies for detecting past patterns of fire events. However, calculations of long fire rotations in Grand Canyon ponderosa pine forests by Baker are not convincing in methodology or assumptions compared with fire-scar evidence of frequent surface fires. Patches of severe disturbance are a possible hypothesis to explain the relatively short age structure at the park, where ~12% fewer trees were older than 300 years compared with another unharvested northern Arizona site. However, mapped patterns of old trees as well as the evidence for frequent surface fire from fire scars, charcoal deposition studies, and evolutionary history are more consistent with the dominance of surface fire prior to *c*. 1880. The most relevant available evidence of fire recurrence at a given point, mean point fire intervals, had median values <16 years at all five study sites, close to filtered composite fire interval statistics (~6–10 years), but much lower than Baker's calculated fire rotation values (55–110 years). The composite fire interval is not a uniquely important statistic or a numerical guideline for management, but one of many lines of evidence underscoring the ecological role of frequent surface fire in ponderosa pine forests.

## Introduction

In previous analyses (Baker and Ehle 2001, 2003) and his letter published in the present issue of *International Journal of Wildland Fire* (Baker 2006), Baker contends that a high degree of uncertainty exists regarding pre-European fire regimes in ponderosa pine forests. We recognize the well-known limitations of fire-scar and other paleoecological and historical methods for reconstructing fire regimes (e.g. Arno and Sneck 1977; Romme 1980; Swetnam and Baisan 1996; Moore *et al.* 1999). Limited data make it difficult to irrefutably 'exclude' the possibility of large severe fires or other hypotheses. However, looking at the balance of the evidence from fire scars and other sources, we disagree with Baker's conclusion that the pre-European settlement ponderosa pine forests of Grand Canyon, Arizona, were characterized by long fire-free intervals and extensive severe fires. Here we respond to Baker's (2006) letter that critiqued two elements of our Grand Canyon fire regime study (Fulé *et al.* 2003): the use of composite fire intervals and detecting high-severity fire.

## Fire intervals

In 2001, Baker and Ehle expanded on previous criticisms of fire-scar methods (e.g. Johnson and Gutsell 1994; Baker and Ehle 2001). They argued that there is an identity between the population mean fire interval (FI) and fire rotation (FR). Baker's (2006) letter compared our fire-scar and historical data for Grand Canyon, calculated an FR value that was longer than the composite FI values presented by Fulé *et al.* (2003), and concluded that the multiplicative correction factors presented by Baker and Ehle (2001) should be used to substantially lengthen the value of FI. Baker's (2006) analysis is not convincing for several reasons: (1) FR was improperly calculated because it did not distinguish fires burning in the ponderosa pine study areas from other adjacent vegetation types; (2) the correction factors rest on mutually contradictory assumptions, illustrating the practical difficulty of combining FR and FI calculations in ecosystems characterized by surface fires; and (3) the FR is not appropriate for the disjunct fires in one of the Grand Canyon study areas, showing that detailed information about fire history is more valuable than summary statistics.

First, Baker's goal in calculating FR was to arrive at an 'accurate' measurement of fire recurrence. The FR calculation is:

(period of years)/(fraction of the study area burned);

thus the denominator is (total area burned)/(total study area). Baker used a list of historical fires from 1924 to 1993,

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presented in table 4 of Fulé *et al.* (2003), to determine area burned, rather than using fire maps (Heinselmann 1973) or a ratio of burned-to-unburned field plots (Niklasson and Granström 2000; Wallenius *et al.* 2004). But the historical fires burned both within and around our study sites, leading to inconsistencies in fire areas *v.* study site areas. On the North Rim, where we developed a fire history by physically sampling 675 ha, Baker calculated an FR statistic on an arbitrarily defined 2566 ha. For example, the 'Dutton' fire in 1988 burned 1332 ha and was detected on four fire-scarred samples from the Powell Plateau study site, but the Powell site was only 315 ha. Thus at least 1017 ha of the fire must have burned outside the study site. If the fuels and terrain outside the sites were similar to those within, this approach might be fine. But Grand Canyon is characterized by its diverse topography. On the South Rim, Baker cut off the inner Grand Canyon from the Grandview buffer. However, he did not similarly try to account for the three North Rim sites, including Powell, that are surrounded on three or four sides by the canyon. This means that fires in chaparral, pinyon-juniper, Mohave desert scrub, and other vegetation types were lumped with ponderosa pine.

The second problem is that Baker relied on mutually contradictory assumptions to reach his conclusion that the Grand Canyon FI values should be multiplied by correction factors. In 2001, Baker and Ehle emphasized that most young trees (in their view, trees $<50$ years old) could not survive fire, so the period between a tree's germination and its first scar, the origin–scar (OS) interval, should be considered a fire-free interval. Where OS values were not known, they estimated that FI values should be multiplied by 1.6 to correct them (Baker and Ehle 2001). Under this reasoning, then, a fire would be defined as all the square meters burned with sufficient intensity to kill all or most ponderosa trees that are $<50$ years old. However, in calculating FR values at Grand Canyon, Baker (2006) used the gross area of the fire perimeters, a total of 478 ha at the Grandview site, for example, despite the fact that these burns had a mosaic of severities including unburned patches. Yet, for these prescribed fires to meet Baker and Ehle's (2001) definition of a fire, every square meter within the 478 ha would have had to burn with at least sufficient intensity to kill most of the trees $<50$ years old. Such a severe prescribed fire would be unlikely in southwestern ponderosa forests, and in fact the age data from the Grandview site show that ponderosa trees with center dates between 1931 and 1970, which ranged between 11 and 50 years old at the time of the burns (1981–1986), made up 86% of the population measured in 1997–1998 (Fulé *et al.* 2002: fig. 2). By the reasoning used to justify correction factors, then, the prescribed burns at Grandview were really not 'fires' at all. We suggest that it is not helpful to advocate correction factors for FI values based on an assumption about fire, ignore that assumption when calculating FR, and then assert that the gap between the answers is proof of the need for correction. This example illustrates the difficulty of force-fitting an oversimplified version of the FR concept, treating fire as a qualitative presence–absence variable, into the complexity of surface fire regimes that include a broad spectrum of severities.

The third reason that Baker's (2006) argument appears unconvincing to us is that it misrepresents some of the twentieth century fire data. Baker (2006) calculated a twentieth century FI for Grandview, noted that it was different from his calculation of FR, and concluded that our results were unreliable. We did not calculate this FI statistic because, in fact, three separate portions of the Grandview site were burned in prescribed fires and should not be integrated into a composite FI. Instead, we provided a thorough discussion that clarified exactly which fires occurred and where they occurred (Fulé *et al.* 2003). On the North Rim, where some twentieth century fires overlapped and where the fires were not management-ignited prescribed burns but rather wildfires or prescribed natural fires (these types of fires, currently called 'wildland fire use fires', are lightning-caused wildfires that are permitted to burn under pre-defined conditions), the fire regime was arguably more similar to the pre-European situation for a number of reasons (Fulé *et al.* 2002, 2003). Here we did calculate the FI and other statistics of the fire distributions through the twentieth century (Fulé *et al.* 2003: table 7). However, our point was to underscore the fact that a seemingly minor change in FI actually 'would obscure key differences between the pre-1879 and post-1879 fire regimes' (Fulé *et al.* 2003).

We do not agree with Baker (2006) that the data in Fulé *et al.* (2003) constitute a 'poor and potentially misleading measure' of the historical fire regime. We did not present an isolated list of FI statistics. Instead, like other recent fire history studies (e.g. Veblen *et al.* 2000; Heyerdahl *et al.* 2001; Stephens *et al.* 2003; Grissino-Mayer *et al.* 2004), we sought to provide as much detail as possible. We used proportional filtering (10%, 25%) to show variability in fire sizes and the likelihood of fires burning a relatively large proportion of the study areas (Fulé *et al.* 2003: table 5). We tested sampling adequacy with cumulative fire date and sample size curves (Fulé *et al.* 2003: fig. 2*a*) to assess whether the sample sizes were close to the asymptote of fire dates (Falk and Swetnam 2003). We subdivided the study areas spatially to see if fire regime interpretations were affected; we reported that the range of study site areas and sample sizes in this particular case did not change the results (Fulé *et al.* 2003).

## Detecting high-severity fire

Our interpretation of past fire behavior was criticized by Baker (2006) as failing to exclude the hypothesis of severe fire because the tree populations were relatively young. Only 7% of the 173 plots in the never-harvested study sites had living trees pre-dating 1600 (Fulé *et al.* 2003) and we found that ~4.5% of pre-European-era trees were $>300$ years old at Grand Canyon (Fulé *et al.* 2002), compared with 16.9% at an unharvested forest site near Flagstaff (Mast *et al.* 1999). Perhaps Baker (2006) felt that we deliberately evaded discussing the possibility of stand-replacing fire in the period before 1700. In fact, however, we commented on the apparently short age structure and introduced the idea of severe fire as a possible hypothesis to explain it (Fulé *et al.* 2002). We did not accept the hypothesis for the reasons described in the paper (lack of even-aged patches, frequent fires from the beginning of the period with adequate sample depth, etc.), but we provided a balanced discussion of the evidence. It is true that fire-scar evidence cannot 'exclude' the possibility that stand-replacing fire or other severe disturbance obliterated the forest prior to the establishment of the oldest trees we encountered. But irrefutable proof is not a reasonable standard of evidence for paleoecological studies. Instead, descriptions of past ecosystem structure and process are assembled from incomplete and fragile archives, bolstered by intersecting lines of evidence from multiple sources.

In the following paragraphs, we present additional information that is relevant to weighing the past role of stand-replacing *v.* surface fires. Baker (2006) suggested that the pooled age data in the companion forest structure study (Fulé *et al.* 2002) could mask even-aged patches created since 1700 covering as much as 77% of the study areas. The forest plot sampling scheme was not designed to disprove a severe fire hypothesis. However, to see if old trees were found only in limited areas, we mapped the oldest trees encountered on the plots (Fig. 1). We sampled on a systematic 300-m grid spacing (1.1% sampling intensity, each mapped tree represents 91 trees per 9 ha). The between-plot spaces are presumably occupied by trees of similar ages, so Fig. 1 should not be interpreted as representing only widely scattered old trees. We also added the only other age data available: the inner ring dates of the fire-scarred trees that were living at the time of sampling (Fig. 1). These dates are minimal estimates, as most cross-sections were not collected to tree pith to reduce damage to the old trees. Figure 1 indicates that old trees were broadly distributed over the study areas, although some plots included only trees that post-dated 1800. Is this due to widespread severe fire, as Baker (2006) suggested, or simply to the chance of encountering old trees in relatively low-density forests under a 1.1% sampling scheme? The largest contiguous area where old trees were not encountered is a group of 9–11 plots (representing 81–99 ha) in the central-western portion of the Grandview site. Past patches of severe fire in this area remain a possible hypothesis, but this portion of the Park was also subject to a documented severe infestation of dwarf mistletoe and some tree cutting to control it (Lightle and Hawksworth 1973; Fulé *et al.* 2002). The limitations of the plot sampling scheme to disprove old tree presence is illustrated in Fig. 2, a scene from within the 'young' area, where old trees are shown in the background right past a plot boundary.

Surface fire regimes are self-reinforcing by preventing the build-up of debris and ladder fuels (dense thickets of small trees). Individual-tree (or 'point') FI data can be used to represent the recurrence of fires at a particular point on the landscape, preventing the conflation of non-overlapping fires that can be a source of error in composite FI calculations. Point FI data should be used with caution, however. They are minimal estimates, as fires do not always scar recording trees (Swetnam and Dieterich 1985). Point FI are influenced by where the best recording trees are distributed across the site and the number of samples (Stephens *et al.* 2003). Our study sites were selected for internal homogeneity, the fire scar samples were dispersed across the landscape, and we had relatively large sample sizes, so the data are as good a representation of point fire return as possible.

Point FI statistics for the Grand Canyon study sites are shown in Table 1 (the fire history data are available at the International Multiproxy Paleofire Database, http://www.ncdc.noaa.gov/paleo/impd/paleofire.html, verified 29 June 2006). Mean point FI values averaged 13–8 years in the pre-fire-exclusion period. Median values, representing the 50th percentile of each distribution, were all below 16 years. These data indicate that fires were frequent not only at the stand level (composite FI) but also the individual tree level (point FI), supporting the hypothesis that frequent burning prevented high fuel build up.

After Baker (2006) applied correction factors to the pre-European settlement fire regime at Grandview, where the all-scar composite FI = 6.9 years (Fulé *et al.* 2003: table 5), he stated that 'at an individual point fire would have recurred on average only every 55–110 years.' This statement is unverifiable because no-one can reconstruct the Grandview fire history at every individual point. But the most pertinent available evidence, in Table 1, shows that the point FI values of the 43 fire-scarred trees comprising the Grandview fire history averaged 18.4 years, median 15.6 years. Only one tree out of 43 fell within Baker's (2006) predicted range, with a mean point FI = 73 years.

Finally, multi-millennium evidence of fire regime characteristics comes from Weng and Jackson's (1999) charcoal sediment study of two lakes on the Kaibab Plateau, located ~20 km from our North Rim study sites, showing a large and sustained influx of charcoal beginning with the arrival of ponderosa pine *c.* 11 000–14 000 years BP. The ponderosa fire pattern contrasted with the pulsed charcoal sedimentation associated with infrequent stand-replacing fires in the preceding centuries when spruce-fir forests predominated. At even longer evolutionary time scales, ponderosa pine displays fire-resistant adaptations that classify it with the frequent-surface-fire pines (Keeley and Zedler 1998).

By asserting that surface fire predominated in the pre-European period, are we saying that past fires never killed trees or groups of trees? Of course not. The fires were free-burning wildfires occurring most commonly during the hottest, driest, windiest part of the year and spreading most widely in drought years (Fulé *et al.* 2003). Such fires kill trees even in open forests with low fuel loads. In an unharvested Mexican forest with a relatively undisrupted fire regime, we reported fire-caused mortality in patches up to several ha in size (Fulé and Covington 1997). The point of contention is not whether fires killed trees but whether the scale of tree mortality reached the level of 'stand-replacing fire'. In the absence of a universally applicable, quantitative definition of stand-replacing fire (Agee 1998), our reasoning is that in addition to frequent fires indicated by the composite FI, point FI data also show that minimal estimates of fire recurrence at points on the landscape averaged <20 years. Stand-replacing fires or other disturbances did not extend over these study areas at the scale of dozens to hundreds of ha since at least 1700 (Fig. 1). And because the ecological factors of species composition and charcoal deposition into local lakes (Weng and Jackson 1999) were relatively similar in the centuries preceding 1700, going back some 10 000 years, it remains a reasonable hypothesis to infer that similar fire patterns prevailed since

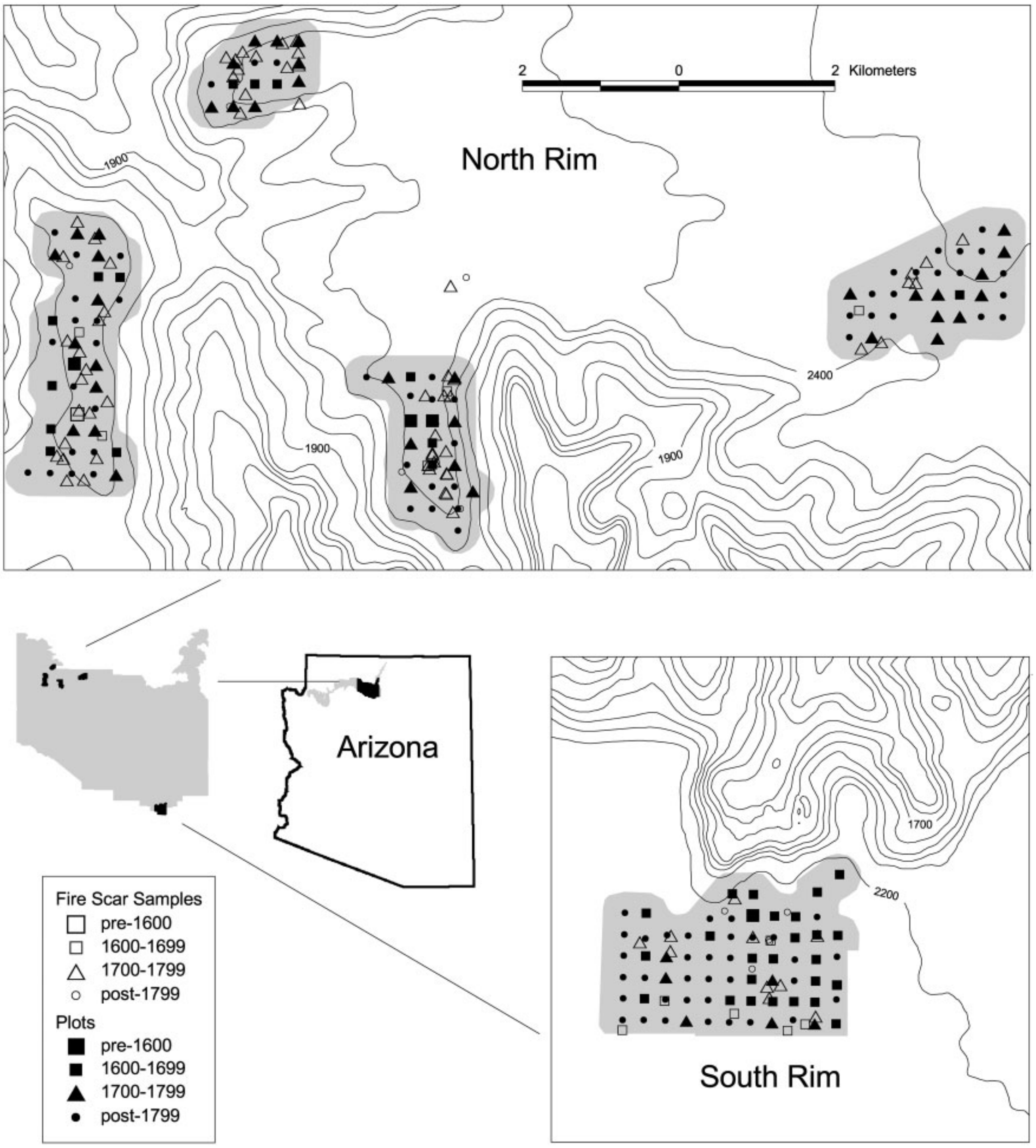

**Fig. 1.** Oldest living trees encountered on sampling plots, and ages of living fire-scarred trees in Grand Canyon National Park, Arizona (Fulé *et al.* 2002, 2003). Sampling intensity was 1.1% (one 0.1 ha plot per 9 ha), meaning that each old tree represents 91 trees per 9 ha. Study sites on the North Rim, from west to east, are Powell Plateau, Fire Point, Rainbow Plateau, and Swamp Ridge. The South Rim study site is Grandview.

the development of the modern climate and plant communities on these sites. In contrast, contemporary fires such as the Rodeo-Chediski fire of 2002 (189 000 ha in eastern Arizona), although still burning with a mosaic of fire severities within the overall perimeter, are distinguished by killing all ponderosa pine trees at scales of thousands of ha (see fire severity mapping in Finney *et al*. [2005] and long-term successional consequences of severe fire in Savage and Mast [2005]).

## Conclusion

Our goal with respect to 'modern calibration' at Grand Canyon was to compare twentieth century fire scars and fire records to see whether fire-scar methods could accurately detect past fires. We concluded that they could, because we detected every fire >8 ha in size that occurred on the study sites since 1924, as recorded in Grand Canyon National Park fire records. This validation lent support to our interpretation of pre-European fire regimes using the same methods.

We agree strongly with Baker and other fire scientists that the FI statistic (or any single statistic) should not be used in isolation of the ecological and historical context. We do not suggest that the composite FI is a uniquely important statistic nor that managers should attempt to use it as a numerical guideline to uniform burning. Rather, the FI together with all the evidence from fire-scarred trees and forest structure should be considered as rich sources of fire information.


**Fig. 2.** 1997 scene from a permanent photo-point on a plot within the largest contiguous area of 'young' forest at the Grandview study site. The group of older ponderosa pine trees, distinguished by large diameters, yellow-colored bark, and large branches with dwarf mistletoe brooms, lies outside the plot, which ended 20 m from the photographer.

Historical fire regimes are used as only one of many sources of information guiding modern management amidst a complex host of concerns including landscape fragmentation, dense fuels, smoke, costs, liability, and invasive and rare species. Although the information is necessarily imperfect, there is consistent evidence of frequent and widespread surface fire in ponderosa pine forests at Grand Canyon. Historical fires, like modern ones, contained severely burned patches and unburned ones. This natural complexity is inadequately captured by a single frequency statistic, such as the composite FI, filtered FI, or average point FI. However, the FI statistics have the advantage of being calculated from measured fire dates using a repeatable mathematical procedure. They can be compared with FI statistics calculated in the same way around the world. Thoughtful ecological interpretations of FI data are available (Agee 1998; Swetnam and Baisan 2003). Therefore we argue these statistics are still useful for quantifying fire frequency in south-western ponderosa pine forests. Baker (2006) did not argue that the FR was just some large number. He stated that he had calculated mathematically accurate values of FR and that the interpretation of a historical regime of frequent surface fires was wrong. However, Baker's FR calculations were based on unconvincing decisions (e.g. inclusion of different vegetation types, contradictory assumptions, lumping together disjunct areas) and were not, in fact, 'accurate' with respect to the data (e.g. comparison of the 55–110-year FR value with the much shorter point FI data, evidence of old trees distributed across landscapes). In contrast, a more reliable FR calculation based on measurement of burned area and fire severity for recent fires would be useful for comparison with fire-scar results.

Since our Grand Canyon work was published, other investigators have completed new studies testing the efficacy of fire-scar methods. Two from Arizona are particularly relevant here. Farris (C. F. Farris, unpublished data) used fire records with much greater resolution than ours to show that fire scars

**Table 1. Mean point fire intervals calculated from fire scar to fire scar for samples from Grand Canyon study sites prior to European settlement**

| Study site | No. fire-scarred samples[A] | Mean point fire interval (year) | Minimum (year)[B] | Maximum (year)[C] | Median (year) |
|---|---|---|---|---|---|
| Grandview | 43 | 18.4 | 6.3 | 73.0 | 15.6 |
| Powell Plateau | 45 | 16.4 | 7.8 | 55.0 | 9.5 |
| Fire Point | 38 | 13.2 | 7.0 | 25.3 | 10.4 |
| Rainbow Plateau | 32 | 15.7 | 6.4 | 60.0 | 12.6 |
| Swamp Ridge | 29 | 16.3 | 7.3 | 30.0 | 13.7 |

[A] Samples had to have >1 fire scar to be included in the calculation; [B] shortest mean point fire interval of all the trees at this study site; [C] longest mean point fire interval of all the trees at this study site.

were successful in capturing not only the dates but also spatial patterns of surface fires in Saguaro National Park. Van Horne and Fulé (2006) carried out a comprehensive collection of data from every fire-scarred tree in a 1 km$^2$ area of Centennial Forest in northern Arizona, showing that the targeted sampling used in our Grand Canyon study (and most south-western fire histories) was an efficient and accurate method for arriving at essentially the same fire regime description as random or other sampling schemes. Both studies also validated the role of proportional filtering (Swetnam and Baisan 1996; Baker and Ehle 2001) in calculating and interpreting fire interval data.

Johnson and Gutsell (1994), Minnich *et al.* (2000), and Baker and Ehle (2001, 2003) provided critical perspectives that have been useful for challenging the assumptions of fire-scar methods. In response, studies such as our Grand Canyon research and the more comprehensive work by Farris (C. F. Farris, unpublished data) and Van Horne and Fulé (2006) have contributed to improving the methods and interpretation of fire-scar-based fire histories. These studies have not provided evidence of infrequent, severe fire in the pre-European record for ponderosa pine, at least in the south-west (see Brown *et al.* 1999 for possible differences in northern Colorado); on the contrary, they have strengthened the inferences of frequent surface fire drawn from fire-scar data. At some point, critiques that use 'uncertainty' as a reason for challenging broad ecological understanding become less than helpful. We will never have certain knowledge of past fire regimes, just as we lack certain knowledge about virtually every ecological process, but that fact does not mean that ecologists and managers should discount what is known about the predominance of frequent surface fire in ponderosa pine forests.

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