Major Decline in Fires in Coniferous Forests – Reconstructing the Phenomenon and Seeking for the Cause

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Steep decline in forest fires about a century ago occurred in coniferous forests over large areas in North America and Fennoscandia. This poorly understood phenomenon has been explained by different factors in different regions. The objective of this study is to evaluate the validity of the four most commonly suggested causes of the decrease in forest fires: fire fighting, over-grazing, climate change and human influence. I compiled the available dendrochronological data and estimated the annually burned proportions of *Pinus*-dominated forests in four subcontinental regions during the past 500 years. These data were compared to the development of fire suppression, grazing pressure, climate and human livelihoods. The annually burned proportions declined over 90% in all studied regions. In three out of the four regions fires decreased decades before fire suppression began. Available drought data are annually well correlated with fires but could not explain the decrease of the level in annually burned areas. A rapid increase in the number of livestock occurred at the same time with the decrease in fires in the Western US but not in Fennoscandia. Hence, fire suppression in Central Fennoscandia and over-grazing in the Western US may have locally contributed to the reduction of burned areas. More general explanation is offered by human influence hypothesis: the majority of the past forest fires were probably caused by humans and the decrease in the annually burned areas was because of a decrease in human caused fires. This is in accordance with the old written records and forest fire statistics. The decrease in annually burned areas, both in Fennoscandia and the United States coincides with an economic and cultural transition from traditional livelihoods that are associated with high fire use to modern agriculture and forestry.

1 Introduction

Frequent forest fires, having pronounced impacts on species composition, tree age, size structures, and nutrient cycling in forests, are considered to be integral part of the ecology of global coniferous forests (Goldammer and Furyaev 1996, Pyne et al. 1996). Widespread distribution of the post-fire regeneration cohorts of trees as well as fire-killed and fire-scarred trees attest to the powerful effects of fires on forests and enable the accurate dating of fires of the past few centuries. In the well-studied coniferous forests of Fennoscandia and North America, the reported point-wise fire intervals (corresponding to the inverses of the mean annually burned proportions) have mostly varied from a decade to a century or somewhat more in the past (Niklasson and Granström 2000, Baker and Ehle 2001, Groven and Niklasson 2005, Zhang and Chen 2007).

In contrast to the ample publicity for the recent years' large forest fires in North America (Stocks et al. 2002, Whitlock 2004, Westerling et al. 2006), most fire-history studies show a dramatic decline in burned areas when approaching the modern times (Niklasson and Granström 2000, Groven and Niklasson 2005, Zhang and Chen 2007, Marlon et al. 2008). In the latter half of the 20th century, in most parts of North America and Fennoscandia, fires have been so rare that the expected fire intervals are now in the hundreds or thousands of years.

The decrease in fire frequency has resulted in considerable changes in forest structure and species composition. In Fennoscandia, for example, dozens of fire-dependent species have become endangered (Rassi et al. 2001, Wikars 2004), and large parts of the forests of the Western US are growing more fully stocked than earlier, which leads to more destructive fires (Allen et al. 2002, Whitlock 2004). Although alarmed by these changes, researchers have paid relatively little attention to the cause of the widespread drop in annually burned areas. Usually authors have offered one or two more or less „likely" explanations, which, however, vary from study to study.

The most common hypotheses presented for the decline in fires have been the following:

1) Fire suppression. The effectiveness of fire suppression has been suggested because of the more or less simultaneous start of fire suppression policy and the decline in fires (Heinselman 1973, Zackrisson 1977). The development of fire suppression was started by newly-established public forest services in the 1860s in Fennoscandia (Niklasson and Granström 2000, Ruuttula-Vasari 2004) and in the 1910s in North America (Pyne et al. 1996). The practices included new regulations concerning the use of fire in forests, education, surveillance of people and fires, and extinguishing of fires. However, fire suppression is considered essentially to be an unnatural interference by man in natural forest dynamics, i.e. putting out fires lit by lightning.

2) Climate change. Climatic explanation for the decline in burned areas is suggested in Canada. Despite the generally warming trend since the end of the Little Ice Age it has been proposed that the decrease in the annually burned area has been mainly caused by climate change (e.g. Flannigan et al. 1998, Weir et al. 2000, Girardin et al. 2009). There is no doubt that most forest fires occur during dry and hot weather. However, climatic warming does not necessarily mean more risky fire weather. In southeastern and southwestern Canada, monthly drought code (MDC) in July indicates increasing summer moisture during the 20th century and this has been associated with the decrease in fires since the latter half of the 19th century (Girardin et al., 2009). It has been also proposed that the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) of the sea surface temperatures could explain the long-term trends in fire regimes in that the positive phase of AMO promotes widespread synchronous fires in western North America and the positive PDO does so in northern North America (Kitzberger et al. 2007, Fauria and Johnson 2008).

3) Livestock over-grazing. In the Western US it is suggested that grazing by cattle and sheep in the end of the 19th century reduced the amount of fire-carrying vegetation, and that this contributed to the observed reduction in the annually burned areas (Savage and Swetnam 1990, Heyerdahl et al. 2001, Grissino-Mayer et al. 2004).

4) Past human influence. Many fire-history studies both in Fennoscandia and North America

have suggested that a considerable proportion of past fires have been caused by humans and that the reduction in such fires has contributed at least to the observed decrease in number of fires (Niklasson and Granström 2000, Weir et al. 2000, Evett et al. 2007, Granström and Niklasson 2008). In North America, this explanation has usually been coupled with the climatic hypothesis, which has, however, been seen as the main reason for the decrease in the annually burned areas. In Fennoscandia, more careful handling of fire has not been clearly separated from the effects of extinguishing fires.

It is improbable that all the offered explanations are correct or that they are valid everywhere. More likely, the variety of explanations reflects the lack of comprehensive study of the topic that would cover wide spatial and temporal scales. My objective is to clarify the timing and magnitude of the decline in forest fires and discuss the validity of the four most commonly suggested causes for it.

2 Materials and Methods

I evaluated validity of the hypotheses above with extensive data sets from four intensively studied coniferous forest regions in two continents representing temperate and boreal vegetation zones. In order to study the temporal and spatial patterns of the major decline in fires, the annually burned areas for the past 500 years were reconstructed using fire-scarred trees. In the studied sites in the Northwest and Southwest US, the dominant species is *Pinus ponderosa* Dougl. (Laws.) and in Fennoscandia *Pinus sylvestris* L.. These long-living and widely distributed tree species form fire scars, which do not decay easily and allow accurate dendrochronological dating of past fires. Although results do not represent systematic sample of all forest types, this does not invalidate the analysis since I am focusing on the magnitude and timing of the decline in fires.

Data for the Western US were downloaded in November 2008 from the International Multiproxy Paleofire Database (http://www.ncdc.noaa.gov/paleo/impd/paleofire.html). A total of 6069 fire-scarred trees from 289 sites in the western

states, i.e. all studies where 'recording years' of trees were marked separately from non-recording years, were included in the study (Supplementary data, Table S1). The trees were usually considered susceptible to scarring, and hence to recording fires, only after they had got the first fire scar.

The majority of the downloaded fire-scar data originate from two separate regions, i.e. Northwest US and Southwest US (Fig. 1), having their own synchronous fire regimes (Kitzberger et al. 2007). Annually burned proportions of the forests in the entire western US and its sub-regions were estimated by dividing the number of fire-scarred trees by the number of recording trees in each year. The compilation of the fire-scar data was conducted with the help of fire-history analysis and exploration software FHAES compiled by Henri Grissino-Mayer from the University of Tennessee.

In Fennoscandia, the annual fire data were generally not available, and therefore the annually burned proportions of forests were calculated as means of different studies for successive 25-year periods starting from 1501. The fourteen reviewed Fennoscandian studies included at least 3301 trees from 1011 locations (Supplementary data, Table S2). The data were acquired either from the authors or from the published tables and graphs. Kohh (1975) reported his data in 50-year periods, which were divided into two 25-year periods with the same annually burned proportions. The spatially small and adjacent studies by Lehtonen and Kolström (2000) and Wallenius et al. (2004) were averaged before calculating the mean between the other the studies.

The tree-ring-based reconstructions of burned proportions were compared with the fire statistics from the same regions. Finland has one of the longest nation-wide forest fire records in the world; they begin from the year 1865 for the State forests and from the year 1952 for the whole country (Osara 1949, Year book of forest... 1992). The earliest extensive forest fire statistics in the US are from the year 1880 (Sargent 1884). Beginning from 1906, forests fires have been recorded in the US National Forests, which are located for the most part (80%) in the western states. These data were obtained from the Fire and Aviation Management website (http://fam.nwcg.gov/fam-web/weatherfirecd/fire_files.htm)

for the period 1970–2007 and prior to that as paper copies of annual reports (National Forest Fire Report 1938, 1940–1941, 1948–1959, 1969; Annual Fire Report... 1960–1968). Seven annual reports; 1939 and 1942–1947 could not be found. The burned proportions based on these statistics were calculated by dividing the annually burned areas of National Forest lands by the annual acreage of the National Forests (http://www.fs.fed. us/land/staff/lar/LAR07/TABLE_21.htm). Since the National Forests include also rarely- or never-burned areas, the burned proportions of forests can be expected to be somewhat higher than the calculated results.

In order to objectively evaluate the capacity to extinguish forest fires in the Western US, I used inflation adjusted fire control costs (emergency funds excluded) on US federal lands (Historical statistics of... 1975, Large Fire Suppression... 2004). Another option would have been to report milestones of technical development, like the introduction of motorized fire engines and fire fighting aircraft. Studies where the effectiveness of fire suppression have been interpreted from fire-history has little value in resolving the question of what has caused the dramatic decrease in annually burned areas.

In order to test the proposed effects of climatic variables to burned areas, reconstructions of past PDOs (MacDonald and Case 2005) and AMOs (Gray et al. 2004) were acquired from the World Data Center for Paleoclimatology (ftp:// ftp.ncdc.noaa.gov/pub/data/paleo/treering/recon-structions/pdo-macdonald2005.txt, ftp://ftp.ncdc. noaa.gov/pub/data/paleo/treering/reconstructions/ amo-gray2004.txt). The most recent and most extensive one were selected from the several available PDO reconstructions. The World Data Center for Paleoclimatology also provides annual Palmer's Drought Severity Index (PDSI) reconstructions for the past centuries (Cook et al. 2004) over a grid covering the entire US (http://www. ncdc.noaa.gov/paleo/newpdsi.html). The PDSI gives estimates for the cumulative departure of soil moisture content using monthly temperature and precipitation data and potential evaporation. Negative values (usually down to –6) denote drought and positive values wet conditions. The annual mean of the PDSI values of the grid points 43, 44, 55, 56, 68 and 69 was computed to serve
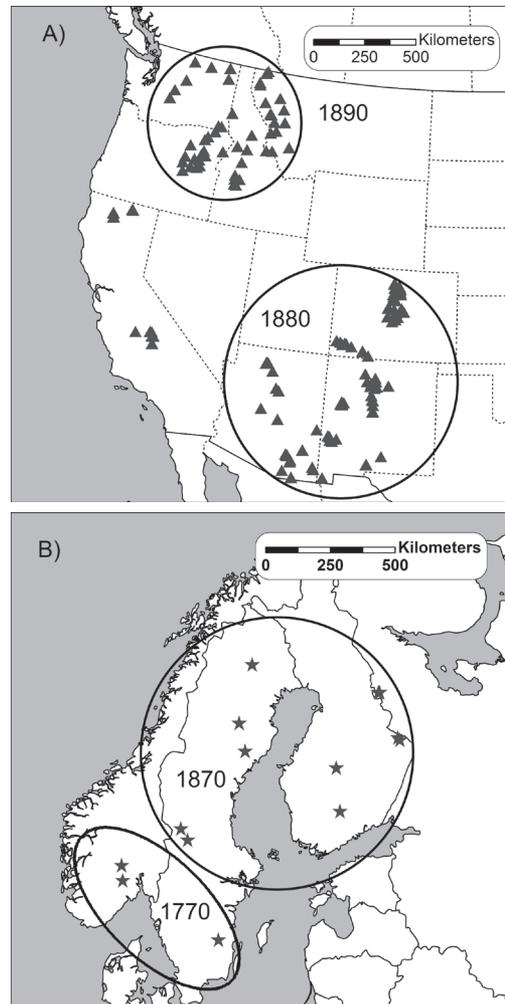

Fig. 1. The locations of the four subcontinental regions in A) the Western US and B) Fennoscandia where the fire histories were reconstructed. The triangles denote the sampling locations in the Western US and the stars indicate the study areas' mid-points in Fennoscandia. Approximate date for the steepest decline in annually burned areas is given for the regions.

as a regional drought index in the Northwest US. In the case of the Southwest US I used the grid points 104, 105, 118, 119, 120, 131, 132, 133, and 134.

PDSI reconstructions were not available for Fennoscandia. Instead reconstructed summer

temperature (Luterbacher et al. 2004) and precipitation (Pauling et al. 2006) were obtained from the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI) (http://climexp.knmi.nl/). In addition, instrumentally measured mean summer (June, July and August) temperature and summer precipitation sums for the Western US and Fennoscandia were downloaded from the KNMI. Six inland stations in the Western US (WMO station codes: 72681, 72483.3, 72376.2, 72269.1, 72653.5, 74530.3) were selected because they have nearly complete weather records dating back to 1868. In Fennoscandia, the selected temperature stations (WMO codes: 1489.1, 2464, 2974) have measured temperature continuously at least since 1829 and precipitation stations (WMO codes: 2458.1, 2974, 2627.2) since 1845. Instrumentally determined sea surface temperature indices PDO and AMO were also downloaded from the KNMI (Mantua et al. 1997, Kaplan et al. 1998).

Pearson's correlations of all the climatic variables with the reconstructed burned proportions were tested in 25-year resolution in Fennoscandia and in annual resolution in the Western US. For the annually burned proportions in the Southwest US it was possible to build a well-fitting generalized linear model (GLM) using the quasi-likelihood with the variance function of the Poisson distribution and the logarithmic link function. The predictors were the same year's and the previous years' PDSIs.

Density of cattle was calculated by dividing the number of cattle by the surface area of the area in question. Annual number of cattle in the first of January in US for the period 1867–2007 was obtained from the National Agricultural Statistics Services, United States Department of Agriculture (http://www.nass.usda.gov/). Averaged cattle density in Arizona, New Mexico and Colorado were compared to the reconstructed annually burned proportions in the Southwest US (Fig. 1). Correspondingly data from Washington, Oregon, Idaho and Montana were combined and compared to the forest fires in the Northwest US. Cattle data from Finland is available from the beginning of 19th century (Suomen tilastollinen vuosikirja 1925, 1940, Soininen 1974, Statistical Year Book... 1985).

Comprehensive data on the number of human-caused forest fires in the distant past is lacking. Fire statistics including the proportion of human-caused fires are available since 1906 for the US National Forests (National Forest Fire Report, 1938, 1940–1941, 1948–1959, 1969; http://fam.nwcg.gov/fam-web/weatherfirecd/fire_files.htm). During the first three decades the total number of annually recorded fires steeply increased mainly because of improving recording. In 1936 Forest Service started the 10 a.m. policy (meaning that all fires must be put out before 10 o'clock in the next morning) and as a result at least record keeping of fires was arguably nearly complete. Since that time there is no long-term trend in the record of lightning fires in US National forests, but instead there is a significant decreasing trend ($r = -0.55$, $p < 0.001$) in the number of human caused fires.

I suggest that the ratio of human caused fires to lightning fires can be used to show changes in the human contribution or ‚human factor‘ on forest fires. The annual ratio of the number of human caused fires to five year running mean of lightning ignited fires was calculated from the data and it's correlation to annually burned proportions was tested. The problem with the fire statistics from the National Forests is that they do not extent to the early times with excessive fires. To get a data point in the 19th century I calculated another variable by using decadal resolution and by adding the earliest fire statistics from the 11 western states of US (Sargent 1884).

Estimates of the annually slash-and-burn cultivated land in Finland (Heikinheimo 1915), combined lumber exports from Finland (Ahvenainen 1984) and Sweden (Skogs-styrelsens underdåniga... 1879, Ilvessalo and Jalava 1931) and lumber production of western tree species (‚douglas fir‘, ‚western pine‘, ‚hemlock‘ and ‚redwood‘; (Wright 2006) in the US were also used to demonstrate the period of fast transition from traditional fire-causing livelihoods to modern agriculture and forestry. In connection with the modern land uses, forest fires are undesirable.

3 Results

In central Fennoscandia and the Western US, the mean annually burned areas in *Pinus*-dominated forests diminished between 1850 and 1950 to less than one tenth of what they had been at least since the 16th century (Figs. 2 & 3). In southern Fennoscandia, similar dramatic reduction took place already before the end of the 18th century. Detailed recording of fires began only after most of the reduction in mean annually burned area had already taken place. Annually burned proportions in the US National Forests correlate well with the reconstructed fire history in the Northwest US (Table 1). Also in general the available fire statistics are consistent with the results of the fire-scar-based reconstructions of the burned proportions (Fig. 3). Somewhat higher values in the reconstructions as compared to those in the fire statistics could be expected because the sampling sites in the fire-history studies have often been subjectively selected to include a good sample of fire-scarred trees, and therefore possibly more frequently burned stands than the average of the region. *Pinus*-dominated forests also tend to burn more often than forests dominated by other species.

In three out of the four regions, the majority of the reduction in annually burned areas occurred at least two decades before the onset of wide-scale public fire-suppression actions (Figs. 2–4). As is demonstrated by the fire-suppression costs reported for federal lands in the United States (Fig. 3), the resources for extinguishing fires were minuscule before World War II compared to what they are today. Annual fire suppression costs (emergency funds excluded) do not significantly correlate with the annually burned proportions over the whole suppression period in the Western US (Table 1). However, the significant negative correlation for the period 1912–1969 indicates that increasing investment to fire suppression may have reduced annually burned areas in the 1930s and 1940s.

I tested the correlations between several climatic indices and variables, such as summer precipitation and summer temperature, with the proportions of burn-over area in the Western US and Fennoscandia, but all except one (see below) were statistically non-significant across the decline in fires and also before the decline (Figs 2 & 3, Table 1). Lack of annual resolution in the Fennoscandian fire data probably impeded finding of any significant correlation in Fennoscandia. The only statistically significantly correlating climatic variable was PDSI, which could be studied solely in the US with long-term reconstructions being available there. The correlations between PDSI and the burned proportion were statistically significant across the whole period including the dramatic decline in fires (Table 1), but for the period before the reduction (1600–1850) the correlation coefficients were higher, being –0.44 (p < 0.001) in the Northwest and –0.53 (p < 0.001) in the Southwest of the Untied States.

It was possible to build a model for the annually burned proportion in the Southwest US, which explains very well (r = 0.80, p < 0.001) the inter-annual variation in the burned proportions during the period 1600–1799 into which it was fitted (Fig. 4). The model has the form

$$E(y_t) = a_t, \ln(a_t) = 3.71 - 0.349 D_t + 0.232 D_{t-1}, \mathrm{var}(y_t) = 3.71 a_t \qquad (1)$$

where $E(y_t)$ is the expected value and $\mathrm{var}(y_t)$ is the variance of the modelled burned proportion y_t (‰) during year t. D_t is the Palmer's Drought Severity Index during the same year and D_{t-1} is the same index in the previous year. The drier the summer was the more area was burned but the previous years' effect was the opposite. For the period 1800–1879, the model was able to predict the annually burned proportion well (r = 0.72, p < 0.001), but beginning from 1880 the predicted values were systematically higher than the burned proportions (Fig. 4).

The rapid increase in the number of domestic livestock coincides with the beginning of the reduction in the burned areas in the Western US (Table 1, Fig. 5). The highest correlation (r = 0.50, p < 0.001) between the density of cattle and burned proportions was found in the Southwest US. In Finland, the density of cattle was generally higher and increased more steadily than in the Western US. Around the 1860s and 1870s when annually burned areas decreased sharply there was not any corresponding change in the number of cattle.
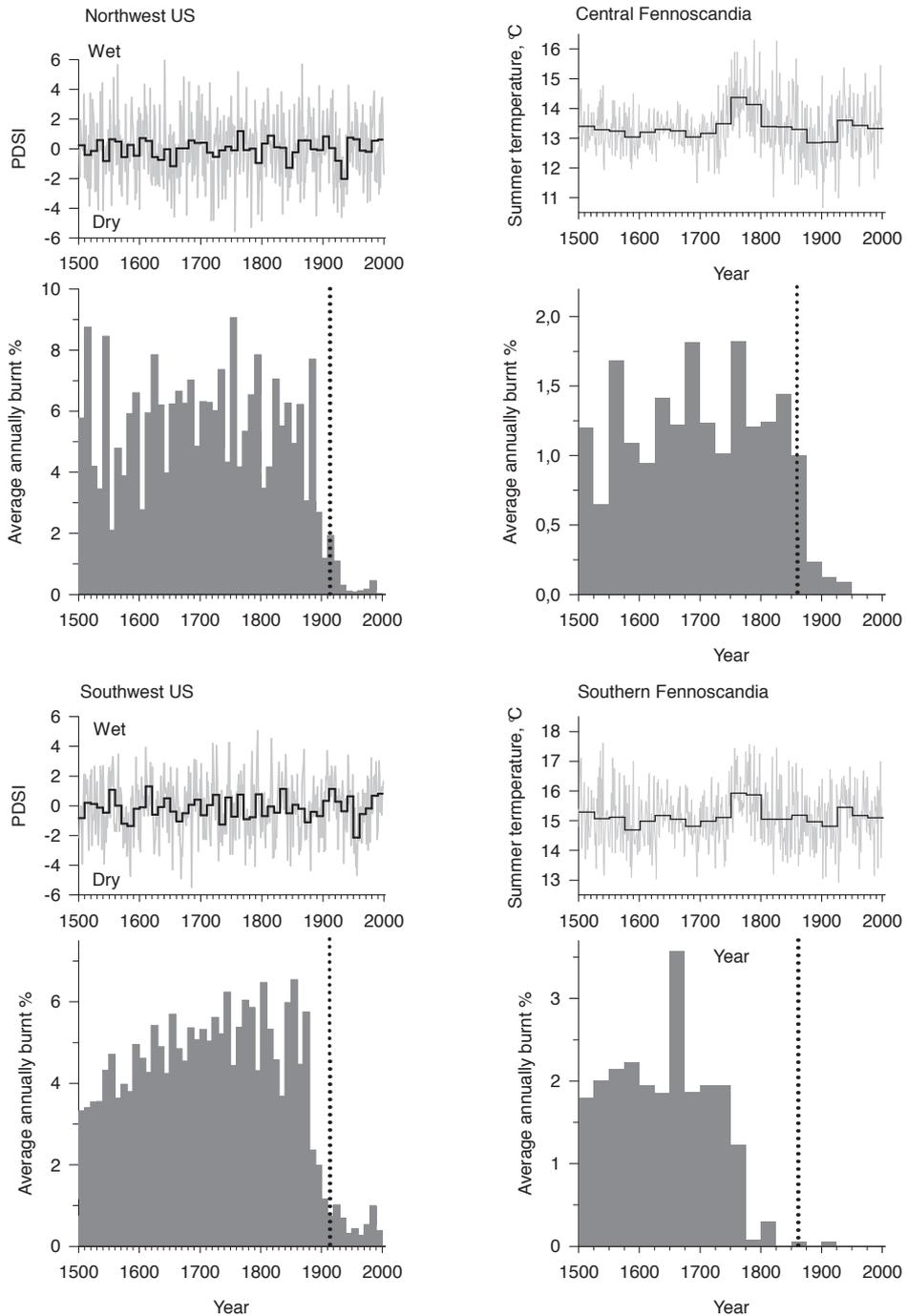
Fig. 2. Tree-ring-based reconstructions of the summer temperature, precipitation and PDSI and fire histories for the past 500 years in four intensively studied subcontinental regions in northern coniferous forests. Average annually burned proportions of the study sites are shown in decades in the two regions in US, whereas in Fennoscandia the available data only allowed computation of the average of the annually burned proportions in 25-year periods. The dotted vertical line denotes the start of the fire suppression policy.

Table 1. Correlation matrix between burnt proportions versus different climate variables and human factors. P-values are Bonferroni corrected and statistically significant correlations are highlighted with grey background. Correlations were calculated for the latest four centuries or as far as the data was available.

		Burnt US	Burnt NW	Burnt SW	Burnt NF	Model SW	Prec. JJA	Temp. JJA	AMO ins.	AMO proxy	PDO ins.	PDO proxy	Logging
Burnt US (All US data)	Pearson Correlation		0.049	0.169	0.226	-0.014	-0.102	0.030	0.125	-0.075	-0.132	-0.052	-0.444
	Sig. (1-tailed)		1.000	0.026	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000
	N		400	400	87	400	132	132	149	391	120	397	97
Burnt NW (Nortwest US)	Pearson Correlation	0.049		0.062	0.754	-0.054	-0.096	0.014	0.135	-0.056	-0.074	0.011	-0.403
	Sig. (1-tailed)	1.000		1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.002
	N	400		400	87	400	132	132	149	391	120	397	97
Burnt SW (Southwest US)	Pearson Correlation	0.169	0.062		0.131	0.615[a	-0.031	0.142	0.068	-0.037	-0.157	-0.098	-0.354
	Sig. (1-tailed)	0.026	1.000		1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	0.014
	N	400	400		87	400	132	132	149	391	120	397	97
Burnt NF (National Forests)	Pearson Correlation	0.226	0.754	0.131		0.036	-0.192	0.165	0.090	-0.147	-0.016	0.283	-0.206
	Sig. (1-tailed)	1.000	0.000	1.000		1.000	1.000	1.000	1.000	1.000	1.000	0.334	1.000
	N	87	87	87		87	93	93	94	78	94	84	84

		PDSI NW ins.	PDSI NW prox.	PDSI SW ins.	PDSI SW prox.	Cattle	Cattle NW	Cattle SW	Fire control	Fire control[b	Human factor[c	Human factor[d
Burnt US (All US data)	Pearson Correlation	0.116	-0.100	0.047	-0.079	-0.489	-0.482	-0.487	-0.134	-0.567	0.203	0.964
	Sig. (1-tailed)	1.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	0.000	1.000	0.000
	N	130	400	130	400	133	133	133	88	58	87	11
Burnt NW (Nortwest US)	Pearson Correlation	-0.118	0.371[a	0.025	0.063	-0.355	-0.361	-0.330	-0.228	-0.450	0.610	0.967
	Sig. (1-tailed)	1.000	0.000	1.000	1.000	0.001	0.001	0.004	1.000	0.015	0.000	0.000
	N	130	400	130	400	133	133	133	88	58	87	11
Burnt SW (Southwest US)	Pearson Correlation	0.148	0.046	-0.084	-0.440*	-0.459	-0.426	-0.509	-0.001	-0.367	0.118	0.873
	Sig. (1-tailed)	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	0.169	1.000	0.017
	N	130	400	130	400	133	133	133	88	58	87	11
Burnt NF (National Forests)	Pearson Correlation	-0.312	-0.375	-0.108	-0.047	-0.213	-0.248	-0.134	0.245	-0.483	0.518	0.214
	Sig. (1-tailed)	0.097	0.009	1.000	1.000	1.000	0.757	1.000	0.913	0.012	0.000	1.000
	N	91	91	91	91	87	87	87	84	51	94	10

[a] prior the decline in fires correlation was higher, see text and Fig. 4, b) for the period 1912–1969, c) not including Sargent's (1884) data, d) decadal averages, including Sargent's (1884) data
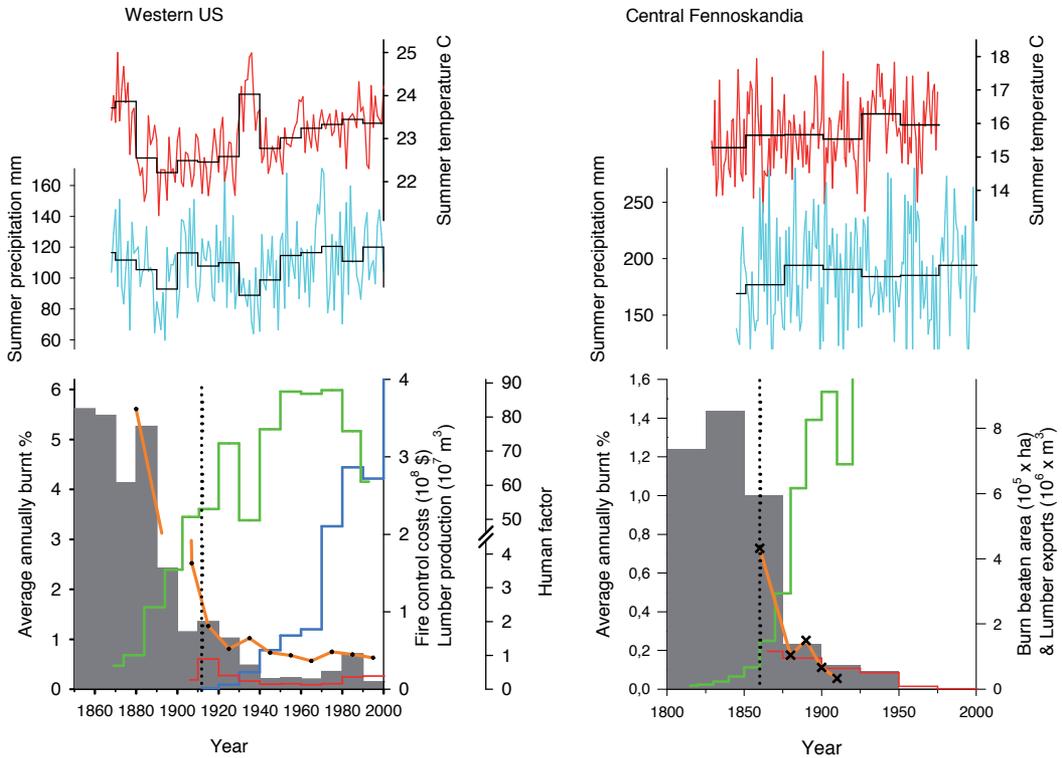
Fig. 3. Instrumentally measured climatic variables and the fire scar based reconstructions of the decrease in fires in western US and Fennoscandia. For comparison, the mean annually burned proportions according to fire statistics from US National Forests and Finnish State Forests are marked with a red line. The vertical dotted lines denote the onset of fire suppression implemented by the national forest services, and the blue line denotes the fire suppression costs on US Federal lands in $2007 money. The burned proportions are indicated with grey fill. The exponential development of the lumber industries in the Western US and in Sweden and Finland are marked with green lines. The proportion of human-caused fires (orange line with black dots) in 1880 is from the eleven westernmost states of US and in 1906–2000 from the National Forests as decadal averages. The slash-and-burn cultivated area (orange line with crosses) is from Finland.

The human factor (ratio of human caused fires to lightning fires) correlates very well with the burned proportions in decadal resolution (Table 1, Fig. 3). According to the oldest fire statistics from the western United States in 1880, there were about 80 times more human-caused wildfires than lightning fires. In the beginning of the 20th century the human factor was 2–4 but decreased to about 1 in the mid-20th century. The oldest fire statistics by Sargent (1884) are far from being complete. However, the correlation coefficients remain practically the same ($r > 0.92$, $p < 0.001$) even if we assume that 90% of lightning fires in Sargent's data were incorrectly assigned to human

origin (human factor thus being only about 8 in 1880) (Fig. 3). If we exclude this earliest data point, the correlation is lower but still significant in the Northwest US (Table 1).

4 Discussion

4.1 Fires Decreased before Effective Suppression

The annually burned proportions abruptly decreased into less than one tenth of the earlier
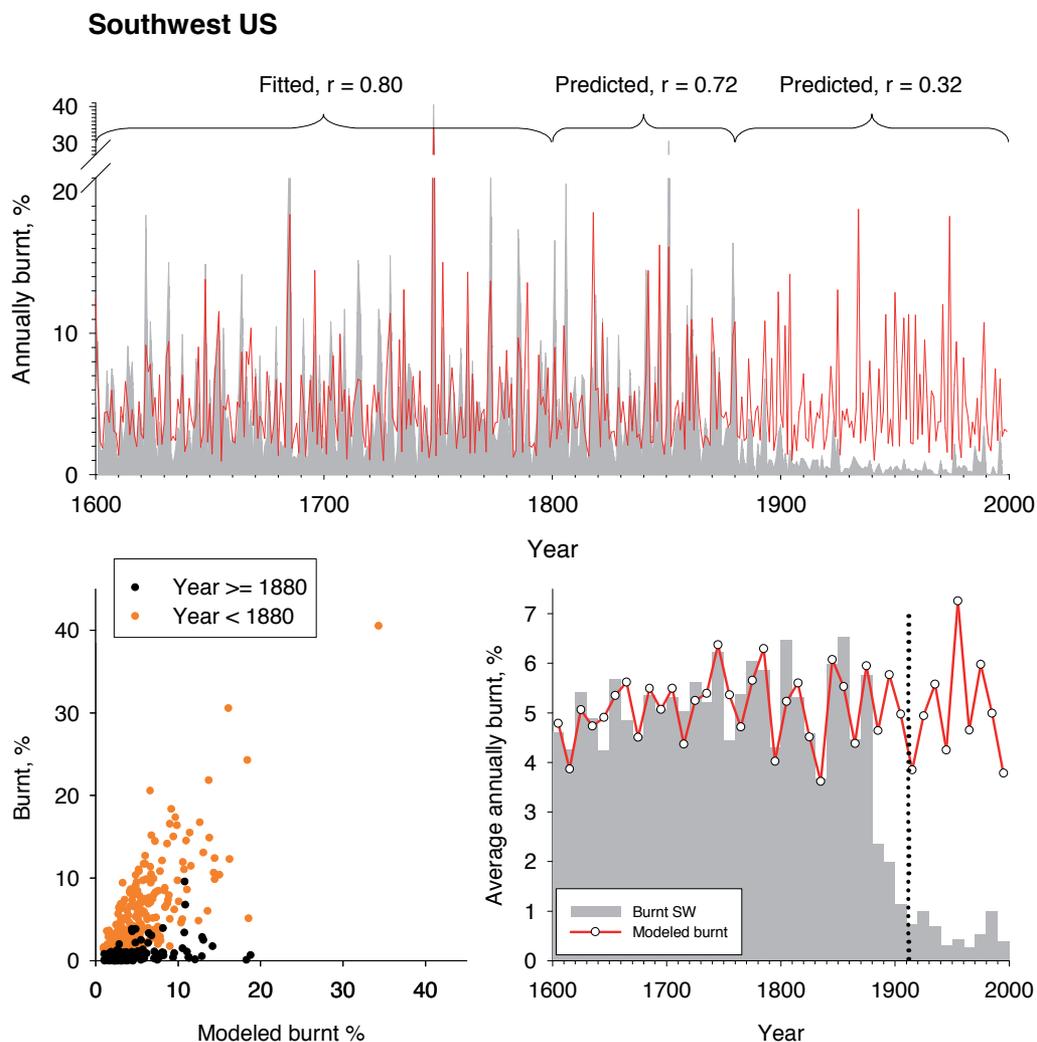
Southwest US

Fig. 4. Reconstructed (gray fill) and modeled (red line) annually burned proportions of study sites in the South-west US. Annually burned proportions were modelled based on the same and the previous years' PDSIs. Data from the period 1600–1799 was used for fitting the model. The correlation between the modelled and the reconstructed burnt values was excellent until 1880. The dotted vertical line denotes the start of the fire suppression policy.

level in all studied regions. The magnitude of the reconstructed widespread decrease in burned areas more than a century ago far exceeds the recent decades' increase in burned areas in the Western US (Figs. 2 and 3). Fire suppression costs did not correlate with burned proportions over the whole suppression period but the correlation between the fire suppression costs and burned proportions was significant during 1912–1969 (Table 1). In

the 1970s the US Forest Service fire suppression strategy was changed from the 10 A.M. policy to 'fire by prescription' (Pyne et al. 1996) and that may have contributed to the recent decades' increase in annually burned areas in the Western US which occurred despite the concurrent consid-erable increase in fire-suppression cost.

Modern fire suppression is considered to be highly effective in Fennoscandia, whereas in
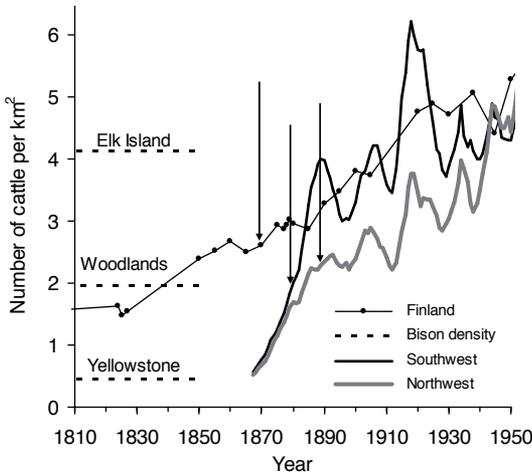
Fig. 5. Density of cattle in three regions. Arrows point to the moment when annually burned proportions declined the most steeply. The current bison densities in Yellowstone and Elk Island National Parks are given with dotted horizontal lines. The general estimate for pre-white-man bison density in the 'woodlands' is by Ernest Thompson Seton (Dary, 1989).

Canada the debate is still on-going as to whether or not modern-day fire suppression is effective (Bridge et al. 2005). Even if current fire suppression practices are effective, the fact that burned proportions decreased for decades before any extensive fire-suppression programs were applied undermines the hypothesis that extinguishing lightning fires was the main cause for the reduction in annually burned areas more than a century ago in the Western US and southern Fennoscandia. It was only in central Fennoscandia that the decline in fires did not clearly precede the launching of fire-suppression programs. However, it is not clear how effective fire fighting was possible in remote locations in the 19th century without motorized equipment. Nevertheless, fires ended also in regions where there were very limited resources to put out fires (Engelmark 1984, Wallenius et al. 2005).

4.2 Inconsistent Climate and Fire Histories

Contrary to the expectations by the climatic hypothesis, I found that the summer temperature and precipitation statistics as well as PDO and AMO do not show statistically significant correlation over the period when the fires decreased, and hence these do not offer a straightforward explanation for the drop in annually burned areas in the Western US and Fennoscandia (Table 1, Figs. 2 and 3). Summer drought correlated significantly with the annually burned area in the Western US, but it could not explain the dramatic decline in fires (Fig. 4). Most of the previous studies, which have proposed that climate variation drives the long-term changes in fire regimes have their data limited either to the 20th century (Fauria and Johnson 2008, Girardin et al. 2009) or to the past (Kitzberger et al. 2007) and therefore they have possibly missed the dramatic decline in fires. Note, however, that in northern Canada and Siberia the decline has obviously not been as pronounced as in the Western US and Fennoscandia (Swetnam 1996, Larsen 1997).

The general climatic trend in the Northern Hemisphere has been warming since the beginning of the 17th century (Moberg et al. 2005). The warming of summers during the recent decades has been associated with the increase in fires in the Western US and the same relationship is expected to apply in future fire regimes (Flannigan et al. 2005, Westerling et al. 2006) with considerable spatial variation (Girardin et al. 2009).

The developed model explained more than half of the variance in annually burned proportions (Fig. 4). The model, which was built on drought reconstructions, predicted sharply an upper limit for the annually burned proportions but there was not any clear lower limit for the annually burned proportion. In some years the burned proportion remained low despite excellent conditions for fires. This suggests that amount of burning was partly limited by small number of ignitions. The good correlation in the Western US between drought (drought is expressed as negative PDSI values) and burned area can be expected from the physics of the combustion as wet fuels do not burn readily. Previous years' droughts had a negative impact on the burned area, which makes sense because during dry years considerable propor-

tions (10–40%) of forests have burned (Fig. 4), but little new vegetation has been formed. However, preceding wet years contribute to the growth of new fine fuels. The same is suggested by Margolis and Balmat (2009). Overall, the good fit and prediction capability of the developed model adds credence both to the annually burned area estimates and the independently reconstructed PDSI in the Southwest US.

As of the 1880s, the previously well-working model no longer correctly predicts the burned areas (Fig. 4), thus making the climatic explanation for the decrease in forest fires problematic in the Western US. The finding that in the past forests mainly burned during dry summers does not tell much about the predominant cause of the fires, which can be either lightning or humans. Unfortunately, the data on past lightning activity is not available. The current frequency of lightning-ignited fires in northern coniferous forests ranges from less than one per year per $10\,000$ km^2 in Northern Finland up to four hundred in the Southwest US (Larjavaara et al. 2005, Kay 2007).

Detailed fire-history studies in Fennoscandia have revealed that past fires have been an order of magnitude more numerous than what could be expected from the present-day frequency of lightning ignitions (Niklasson and Granström 2000, Hellberg et al. 2004, Groven and Niklasson 2005). The only exception is that in the study by Niklasson and Granström (2000) the estimated density of fires prior the 1650s was similar to the current lightning ignition density. However, in their study the number of small fires was probably underestimated due to truncated fire size distribution. In North America there is only one study of this topic from northern Mexico but the result is basically the same, i.e. much more fires in the past than could be expected based on the current lightning fire density (Evett et al. 2007). Possible explanations for the phenomenon are that there has either been a dramatic reduction in lightning-lit fires, which however lacks evidence, or a reduction in fires caused by humans (see below for further discussion).

4.3 Are Cows and Sheep the Best Firemen?

Increasing cattle densities correlated significantly with the decreasing annually burned proportions in the Western US (Table 1). Supposing that excessive grazing in the Western US caused the early decrease in burned areas there, this means that cows and sheep are more effective in preventing fires than firemen because the majority of this decrease occurred prior to the onset of fire suppression (Figs. 2 and 3).

Despite the good correlation, there are a few reasons that make the grazing livestock hypothesis a problematic explanation for the decrease in fires. First, the grazing hypothesis is undermined by a lack of consideration for the effect of wild herbivores. It is postulated that pre-white-man bison densities were equivalent to the number of free-ranging cattle later in the same habitat (Dary 1989). Currently, there are no unregulated bison herds in the US. Nevertheless, hunted populations of bison and elk in Yellowstone and Elk Island National Park in southern Canada are high and comparable to the cattle densities in the Western US (Fig. 5). The high population densities of grazers (up to 15 elks per km^2 in Yellowstone Blacktail Plateau) have certainly modified the vegetation but have not prevented extensive forest fires in the same areas (Singer and Harter 1996, Otway et al. 2007, Hood and Bayley 2008).

Secondly, and somewhat surprisingly, the cattle densities have been generally higher in the past in Finland than in the Western US (Fig. 5), but none have suggested that excessive grazing provides an explanation for the reduction in the annually burned areas in Fennoscandia. This is obviously because the forest floor vegetation in Fennoscandia (and also over large areas in North America) mainly consists of dwarf shrubs, mosses, and lichens. Cattle do not prefer to eat these species, which do, however, act as a fuel in the spreading of forest fires. Neither do cattle eat needle litter and coarse woody debris, which form an important part of the fuel in the Western US forests (Passovoy and Fule 2006, Keyser et al. 2008). Moreover, in Fennoscandia there has not been a similar rapid increase in the number of cattle simultaneous with the dramatic decrease in fires (Fig. 5).

4.4 People Back in the Dock

The decreasing human factor correlates best with the decline in fires (Table 1, Fig. 3). The results suggest that human caused fires dominated the past fire regimes and that the decrease in annually burned areas, both in Fennoscandia and United States coincide with an economic and cultural transition from traditional fire-causing livelihoods such as slash-and-burn cultivation to modern agriculture (including cattle breeding) and forestry (Table 1, Fig 3). In the 19th century, majority of the human-caused fires were related to intentional land clearing and livelihoods such as hunting and pasture burning (Sargent 1884). In Fennoscandia, one important cause of forest fires was slash-and-burn cultivation, which was still common in 1860, but was then dramatically reduced by the beginning of the 20th century (Fig. 3) (von Berg 1859, Heikinheimo 1915).

Prior to the 20th century, explorers, surveyors, foresters and other observers were unanimous on the view that humans were the predominant cause of the excessive forest fires (von Berg 1859, Sargent 1884, Bell 1889, Williams 2003, Natcher 2007). It was both the native people and the settlers who were reported to burn forests for various reasons. The fire use by the American Indians has been studied with some detail (Barret and Arno 1982, Russell 1983, Boyd 1986, Keeley 2002) and fire was certainly versatile tool for them as Lutz (1959) lists 77 different reasons to burn forests and prairies. In the Western US, the decline in forest fires and the cultural transition was accompanied by the Indian Wars and removal of native people to reservations. In Fennoscandia, the change in the livelihoods was more peaceful although some clashes between the authorities and the public did occur. The exceptionally early ending of forest fires in southern Fennoscandia (Fig. 2) coincided with increasing regional industrial demand for timber (Östlund 1993, Groven and Niklasson 2005).

The scarcity of lightning-ignited forest fires in the old reports has in recent years been explained by the ignorance of the observers. For example, Sargent's (1884) pioneer work on forest fires has been overlooked because it includes "too" few lightning ignitions compared to human caused ignitions (32/2983). However, the ignorance hypothesis is problematic because it rejects the observations and requires that the high number of past fires (Niklasson and Granström 2000, Hellberg et al. 2004, Groven and Niklasson 2005, Evett et al. 2007) is explained by dramatic changes in lightning activity, and there is no evidence of this. An alternative explanation for the rarely reported lightning fires in the past is that such fires were "diluted" by the large numbers of human-caused fires. This is more likely explanation because it accepts the primary observations from the past and also explains the unexpectedly high density of the reconstructed past forest fires as discussed above.

A small number of people, if they wish to do so, is capable of burning forests more frequently than the forests would naturally burn (Kay 2007, Granström and Niklasson 2008). Therefore, the crucial questions from forest ecology to the fields of anthropology and history are: What did people want? What were the past livelihoods and how was fire used in the forests? Nowadays, forest fires are considered to be mostly a harmful and unwanted phenomenon. This is mainly because forest fires cause economic losses to forestry, threats to property and lives, and excessive CO_2 emissions. It appears that the past attitude of humans to fires was generally different from the present-day attitude, but nevertheless similarly related to their livelihoods and land uses.

For example, in northernmost Fennoscandia, the indigenous Sámi people were careful with fire because forest fires destroyed reindeer lichens, the winter time forage of their semi-domesticated animal species (Massa 1987, Granström and Niklasson 2008). However, according to most accounts, people's traditions varied from recklessness in the use of fire in forests to intentional burning of certain parcels using sophisticated methods (von Berg 1859, Sargent 1884, Bell 1889, Barret and Arno 1982, Boyd 1986, Williams 2003, Natcher 2007). The traditional uses of fire were numerous and varied from pasture burning to slash-and-burn cultivation and from land clearing to hunting. In addition, unintentional fires were caused for example by campfires, which were regularly left burning (von Berg 1859, Bell 1889).

5 Conclusions

Summer droughts clearly affected annually burned areas in the past in the Western US but no evidence was found that the decrease in annually burned areas in the Western US and Fennoscandia would have been because of climatic forcing. Actually, the fact that forests tend to burn during dry spells does not tell much about the ignition causes that can be either human or lightning.

Start of institutionalized fire suppression coincides with the decline in fires only in Central Fennoscandia. Hence, fire fighting may have there locally contributed to the reduction of burned areas already in the 19th century. Increasing number of domestic livestock correlates well with the initial reduction of annually burned areas in the Western US. However, both the grazing and the fire suppression hypotheses raise questions. Firstly, considering the difficulties in modern fire suppression in North America it would be valuable to know the methods and effectiveness of fire suppression in remote locations in Fennoscandia in the 19th century. Secondly, it would be interesting to study 'the anti-fire effect' of domestic animals versus wild herbivores. It is not clear why high population densities of native grazers do not prevent forest fires, if domestic livestock have that effect.

More general explanation for the declined fires is offered by human influence hypothesis: the majority of the past forest fires were probably caused by humans and the decrease in the annually burned areas was because of a decrease in human caused fires. This hypothesis is old but little studied and certainly deserves further research.

Given that humans have lived for thousands of years in coniferous forests, it is difficult to know exactly what the fire regimes would have been without human influence. However, it is probable that the number of fires and the annually burned areas would have been considerably smaller than what they were in the past dendrochronologically well documented period 1600–1850. The past human influence has been so widespread, pervasive and of old origin that it severely hampers the understanding of the natural structure and dynamics of the northern coniferous forests.

Reevaluation of the role of humans on past fires would be important for developing strategies of forest restoration and sustainable management. In addition, to predict climatic change more accurately, we must determine past human influence on fire regimes, and whether northern coniferous forests sequester carbon while recovering from short fire cycles that dominated in the past.

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