Pine Beetle Infestation and Fire Risk in the Black Hills

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1. Introduction

Throughout the Rocky Mountain region of the Western United States, pine trees are currently experiencing a severe infestation by mountain pine beetles (*Dendroctonus ponderosae* Hopkins). This has devastated many pine populations, killing an estimated 3.9 million trees across the Rocky Mountain region in 2007 alone. The Black Hills National Forest in South Dakota and Wyoming has not escaped this infestation, causing concern that the region may be in a state of extreme fire risk due to the large number of dead trees.

John Twiss, then Black Hills Forest Supervisor, in a hearing held by the U.S. House of Representatives in 2002 before the Subcommittee on Department Operations, Oversight, Nutrition, and Forestry of the Committee on Agriculture, testified that

> *Going back to your first question on Beaver Park and Norbeck as compared to the rest of the forest ... It [Beaver Park] is infested with beetles. You see acre after acre – thousands of acres of dead and dying trees, a lot of downfall from hail storms as well as beetle damage, extremely high fire risk, very difficult to walk through and just ripe for a catastrophic fire.*

At the same hearing, Mark E. Rey, Under Secretary, Natural Resources and the Environment, U.S. Department of Agriculture, added that

> *Generally speaking, these forests are out of balance and badly overstocked, as well as, in the case of the Beaver Park area, heavily infested by mountain pine beetles. They should have significantly lower fuel loads on a per-acre basis. If they were in a more natural situation, the fires that would burn through these would be low-intensity ground fires. If an ignition occurs in either of these areas today, it will most likely be a high-intensity crown fire with a potential to spread very quickly and cause a great deal of ecological and, depending on where it spreads to, economic damage.*

Public perception of the enhanced fire risk due to pine beetle infestation was perhaps most compellingly stated by Richard Finn, a landowner in Sturgis, SD, who testified

> *According to Forest Service aerial surveys, the beetle infestation in Beaver Park grew by more than 500 percent between 1998 and 2000 alone. Now, a massive swath of bug-killed trees marks the landscape. To a man, the fire experts with whom I've spoken assess this area as having tremendously magnified fire risk, so-much-so as to be regarded inevitable. They fear the fire intensity these conditions will create, coupled with poor access and steep terrain, will furthermore render any fire ignited in Beaver Park completely unstoppable. The infestation shows no sign of slowing, the fire danger shows no sign of lessening, and as such, I fear each day for the safety of my family.*

Concerns have not lessened since the time of that congressional hearing. As recently as December 12, 2011, in an interview with the *Rapid City Journal*, Black Hills Forest Supervisor Craig Bobzien said

> *We are very concerned about both the large scale of pine beetle epidemic today, and the possible scale of future large wildfires. ... We know that thinning in advance of beetles works. ... Tree stress, often brought on by drought, also weakens the trees natural ability to pitch out the beetles. While drought is less of a factor today, the tree density remains in areas where thinning has not occurred recently.*

Clearly, both the public at large and government officials are worried about enhanced fire risk from dead trees killed by the infestation of mountain pine beetles in the Black Hills National Forest. Just as clearly, considerable expert opinion reinforces these fears. It is, after all, confirmed by both common sense and considerable experience that dead trees quickly lose much of their moisture content and become more flammable. They also lose leaves and branches and are more easily felled by natural forces, factors which can add to the surface fuel load. The net result, according to many forest experts, is that massive tree kill creates a "tinderbox primed for wildfire."

Yet in the case of pine trees killed by mountain pine beetles, this perception seems to be based on intuition and general experience rather than hard science. In a NASA press release,[1] Roy Renkin, Vegetation Management Specialist for Yellowstone National Park, confirmed that this is the

[1] http://www.nasa.gov/topics/earth/features/beetles-fire.html

conventional wisdom but disagreed based on his participation in a detailed study of the specific issue: the relationship between pine beetle infestation and wildfire risk

> *I've heard [the tinderbox analogy] ever since I started my professional career in the forestry and fire management business 32 years ago. But having the opportunity to observe such interaction over the years in regards to the Yellowstone natural fire program, I must admit that observations never quite met with the expectation.*

A growing body of recent research contradicts the conventional wisdom, even showing signs that tree kill from pine beetles can actually *decrease* the risk of wildfire.

At the request of *Friends of the Norbeck*, I agreed to analyze available data on wildfires in the Black Hills National Forest. This document reports the results of that analysis, in addition to some of the recent findings from the scientific literature about the relationship between mountain pine beetle infestation and wildfire risk, and a cursory look at the possibility that changing wintertime temperature may have contributed to the severity of the most recent pine beetle infestation.

2. Data

This study examines several sets of data, including the occurrence of wildfire in the Black Hills National Forest, drought indexes for the region, Spring-Summer temperature changes over the last century, the amount of timber cut each year, and the number of trees killed by mountain pine beetles.

Data on wildfires in the Black Hills National Forest were compiled by the Wildland Fire Suppression divison of the South Dakota Department of Agriculture.[2] The data are for individual fires, recording the year of occurrence and acres burned of each fire for which historical evidence has been found. Data cover the time span from 1910 to 2009. These data constitute a reconstruction based on historical records and are certainly incomplete, with lesser reliability further back in time.

To characterize drought, we tested both the Palmer Drought Severity Index (PDSI), and the Palmer Z-index [Palmer 1965]. PDSI gives a longer-term characterization of moisture conditions, while the Z-index is generally on a more monthly time scale. For both indexes, positive values indicate

[2] `http://www.sdda.sd.gov/WFS/division/statefireinformation/statefirehistory.aspx`

wet conditions while negative values indicate dry (drought) conditions. For both measures, data were specific to South Dakota division 4 (Black Hills) as defined by the National Climate Data Center.

Climatological temperature estimates were taken from monthly station data of the Global Historical Climate Network version 3 for the three stations nearest to the Black Hills National Forest: Rapid City SD, Hot Springs SD, and Newcastle WY.[3] These data include the time-of-observation bias correction which makes them more suitable for long-term climatological study than uncorrected daily station data. To estimate the occurrence of extended hard freeze, uncorrected daily data were acquired for those same three stations from the U.S. Historical Climate Newtork.[4]

Data for annual tree kill due to mountain pine beetles, and for annual timber harvest, were taken from Black Hills National Forest Monitoring Reports, issued by the U.S. Department of Agriculture and the Forest Service.

3. Trend in Fire History

A graph of the acreage burned by individual fires (figure 1) clearly shows that prior to 1959, no fires were recorded with burn area less than 200 acres. This suggests the prior to that time, smaller fires were far more likely to remain undetected, creating a selection effect which strongly biases the count of the number of fires. Therefore we will define fires burning at least 200 acres (nearly a third of a square mile) as "large fires," and limit study to those fires.

The number of such large fires recorded each year is shown in figure 2. There is a definite increase beginning in 1985; it is the first year which shows more than three fires with at least 200 acres burned, and at least since the 1960s it is extremely unlikely that fires consuming nearly a third of a square mile would have gone undetected and unreported. Nine of the years since 1985 have exhibited at least 3 such fires, which only happened twice in prior years, during the severe drought of the 1930s. Both a t-test (p-value 0.0016), and the non-parametric Wilcoxon rank sum test (p-value 0.00022), confirm the difference in wildfire numbers before and after 1985 with undoubted statistical significance.

There is also indication of further increase in the early 2000s, but a comparison of the frequency of fires during the 2000-2006 period to that during the 1985-1991 period (the two recent periods of very high fire activity) fails to establish any difference with statistical significance.

[3] http://www.ncdc.noaa.gov/ghcnm/v3.php
[4] `http://cdiac.ornl.gov/epubs/ndp/ushcn/access.html`

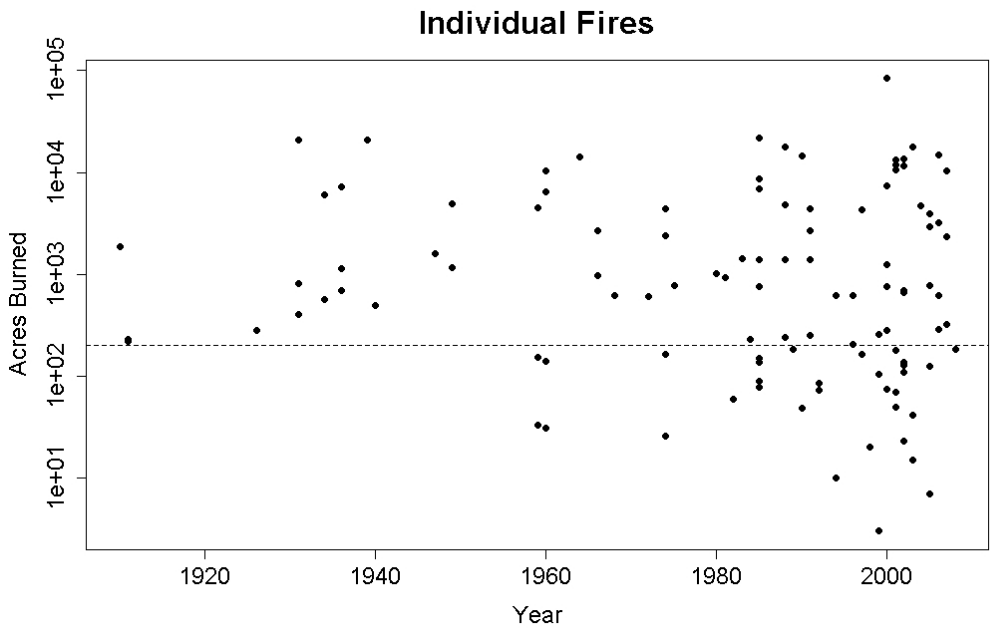

Figure 1: Acres burned by individual fires. Note that the y-axis is a logarithmic axis, and the dashed horizontal line indicates a threshold of 200 acres.

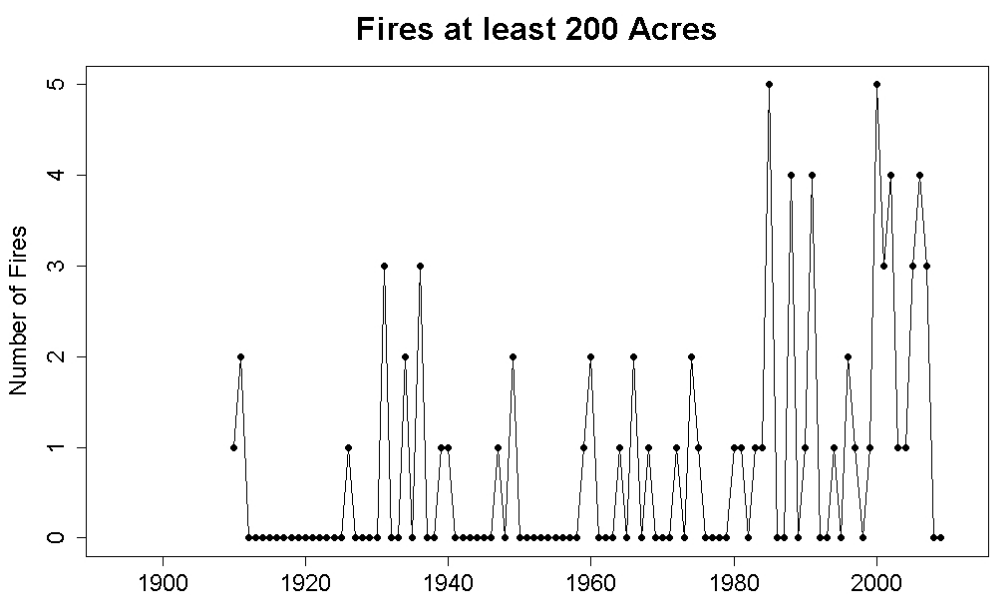

Figure 2: Number of fires per year which burned at least 200 acres.

Therefore according to these data, the overall pattern of wildfire occurrence is one of recent increase, which may be a "step-change" beginning in 1985, or a more steady increase over time.

3.1 Factors Influencing Wildfire

An increase in wildfires beginning in 1985 exists not only in the Black Hills, but throughout the Western U.S. Westerling et al. [2006] surveyed wildfire data since 1970 for the entire region, reporting that "... *large wildfire activity increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons.*" They studied the relationship of wildfire occurrence to both climate and land-use histories, concluding that climate rather than land-use factors dominated the increased fire occurrence, stating "*The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.*"

We therefore studied relationships between the number of wildfires per year burning at least 200 acres, commonly used drought indexes, Spring-Summer temperature anomaly, the total timber harvest, and the number of trees killed by mountain pine beetles. To characterize drought, we tested both the Palmer Z-index and the more commonly used Palmer Drought Severity Index, or PDSI. Spring-Summer temperature anomaly was defined in the same way as Westerling et al. [2006], as the average from March through August. The time series for the number of wildfires burning at least 200 acres, and variables used to predict it, are shown in figure 3 (the figure shows the Palmer Z-index but not the PDSI, because the Z-index showed stronger correlation to the number of large fires per season).

Prior to 1900, tree kill numbers due to mountain pine beetles are exceptionally high, much higher than during the 20th and 21st centuries. This calls these early data into doubt. However, fire data doesn't begin until 1910, so these very early tree-kill data ended up not being used in any of the models tested and therefore had no effect on analytical results. Therefore even if these data are faulty, they cannot have invalidated analysis.

3.2 Form of the Models

The number of fires in a single season can, for very good reason, be expected to follow the Poisson distribution. Therefore we modeled the number of fires as a Poisson process with time-dependent mean value μ which depends on the various predictor variables. Since the mean value of a Poisson process cannot be negative, we first constructed a linear predictor z from the

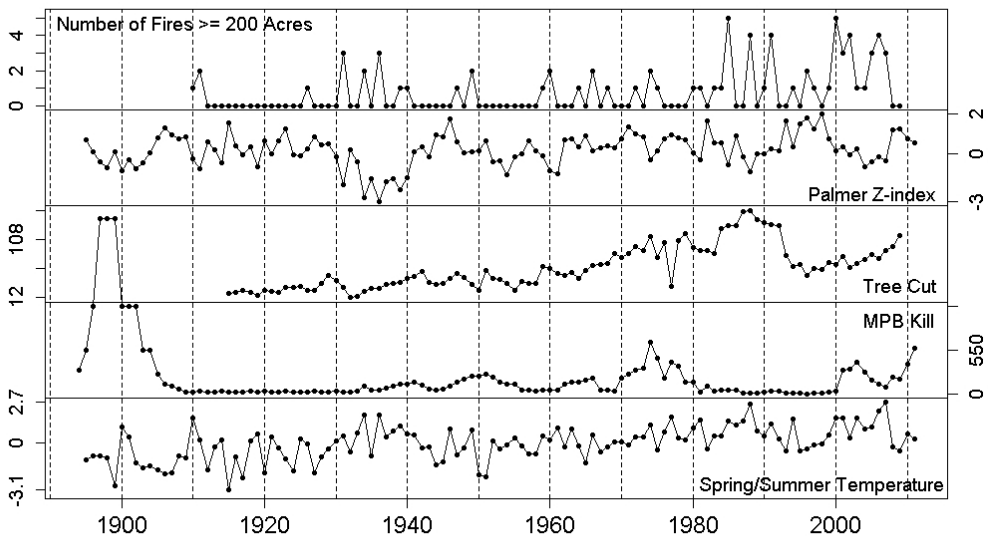

Figure 3: Data used to model fire occurence. Panel 1: Number of fires each year consuming at least 200 acres. Panel 2: Palmer Z-index (positive indicates wet conditions, negative indicates drought). Panel 3: Timber cut (millions of board feet). Panel 4: Mountain pine beetle tree-kill (thousands). Panel 4: Spring-Summer temperature anomaly (average of March through August, deg.C).

predictor variables as

$$z = \beta_o + \beta_1 x_1 + \beta_2 x_2 + ..., \tag{1}$$

where the β_j are the coefficients for the linear predictor and the x_j are the raw predictor variables. This linear variable was then subjected to a hyperbolic transformation to define the mean value μ of the Poisson process

$$\mu = \frac{1}{2}\Big[z + \sqrt{z^2 + \alpha^2}\Big], \tag{2}$$

where α is a further parameter to define the smoothness of the transformation from linear predictor z to mean value μ. The form of the hyperbolic transform is shown in figure 4 for two possible values of the smoothing parameter α. Hyperbolic transformation ensures that the expected number of large fires per season from the model cannot be negative. Large positive z values are approximately equal to the expected number of large fires μ, while for negative values of z the expected number μ approaches zero asymptotically. Models were then fit to actual data by maximum-likelihood estimation.

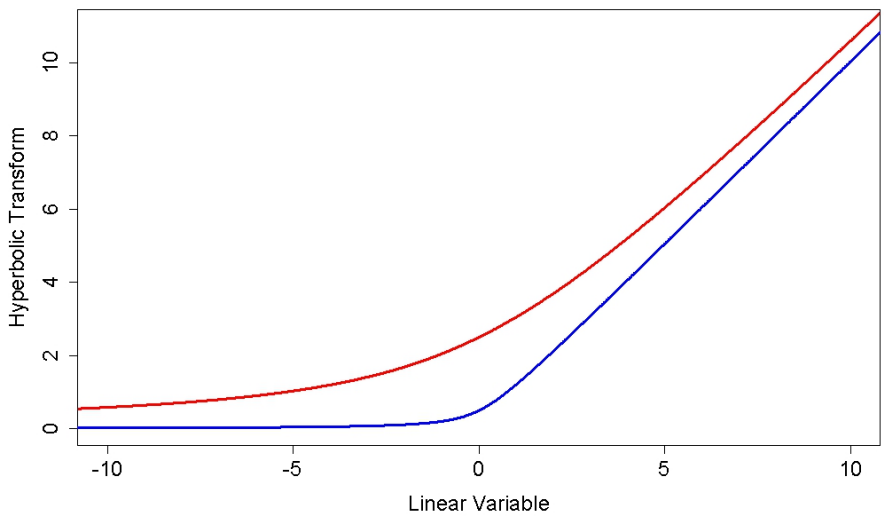

Figure 4: Hyperbolic transformation function for a small value of the parameter α (blue line), and a large value (red).

3.3 Correlations with Predictor Variables

The cross-correlation function of the number of large fires per season with the PDSI is shown in figure 5. There is a clear negative correlation at lag zero, confirming that drought conditions (negative PDSI) enhance the likelihood of large wildfire. However, the cross-correlation function of fires with the Palmer Z-index shows stronger correlation (also negative, also strongest at lag zero), indicating that the Z-index is a better indicator of enhanced fire risk than the PDSI. Therefore in all models of fire occurrence we used the Z-index rather than PDSI.

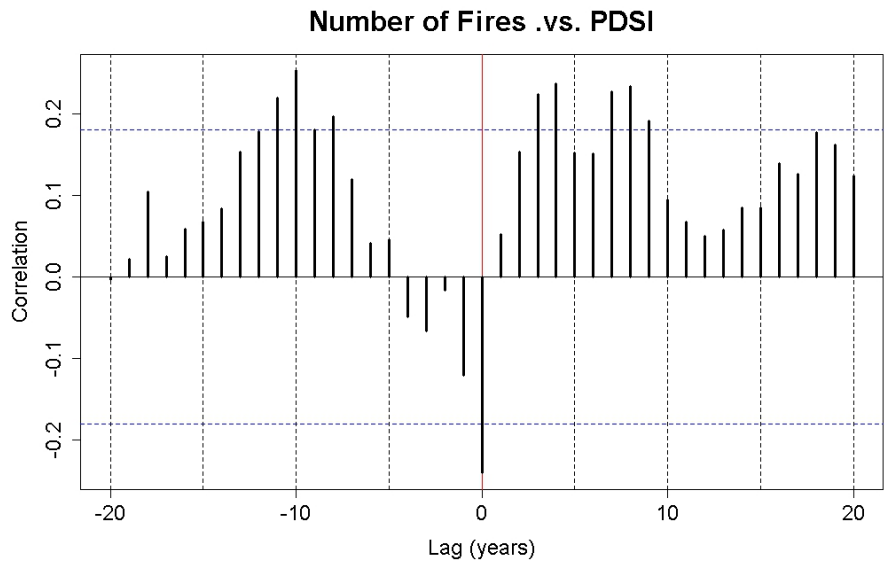

Figure 5: Cross-correlation between the number of fires in the Black Hills National Forest, and the Palmer Drought Severity Index (PDSI). Positive lags indicate that PDSI leads fire occurence.

The cross correlation of fire occurrence with timber harvest is shown in figure 7, and with mountain pine beetle tree-kill in figure 8. Pine beetle tree-kill shows no significant correlation with fire occurrence at any lag. Timber harvest shows positive correlation for large positive lags, suggesting that larger timber harvest actually increases the risk of wildfire, and that the effect is strongest more than a decade after the harvest.

However, there is significant correlation between variables which are known to affect fire risk (drought and Spring-Summer temperature) and those for which the relationship is in doubt (timber harvest and pine beetle tree-kill), so some of the correlation with fire occurrence may be by *proxy*, e.g., timber harvest correlates with Spring-Summer temperature which causes greater fire risk, but the timber harvest is not a causative factor in fire risk. This empha-

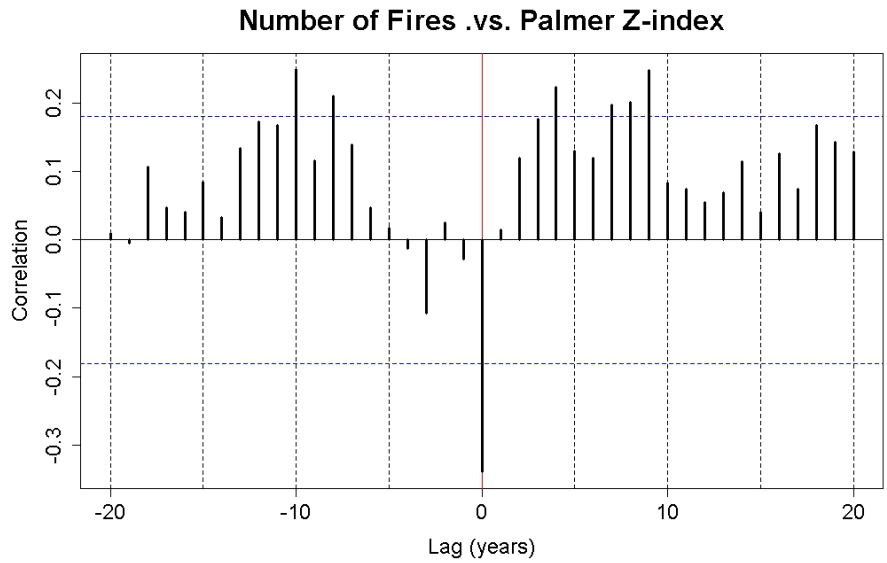

Figure 6: Cross-correlation between the number of fires in the Black Hills National Forest, and the Palmer Z-index. Positive lags indicate that Z-index leads fire occurence.

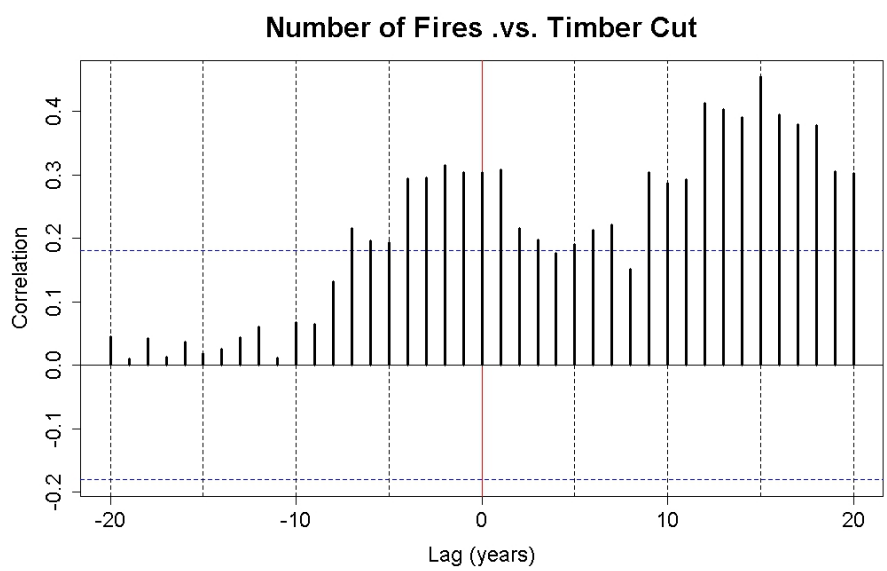

Figure 7: Cross-correlation between the number of fires in the Black Hills National Forest, and timber cut. Positive lags indicate that timber cut leads fire occurence.

sizes the general principle that *correlation is not causation*, and the fact that some variables may make a good predictive model for a given phenomenon,

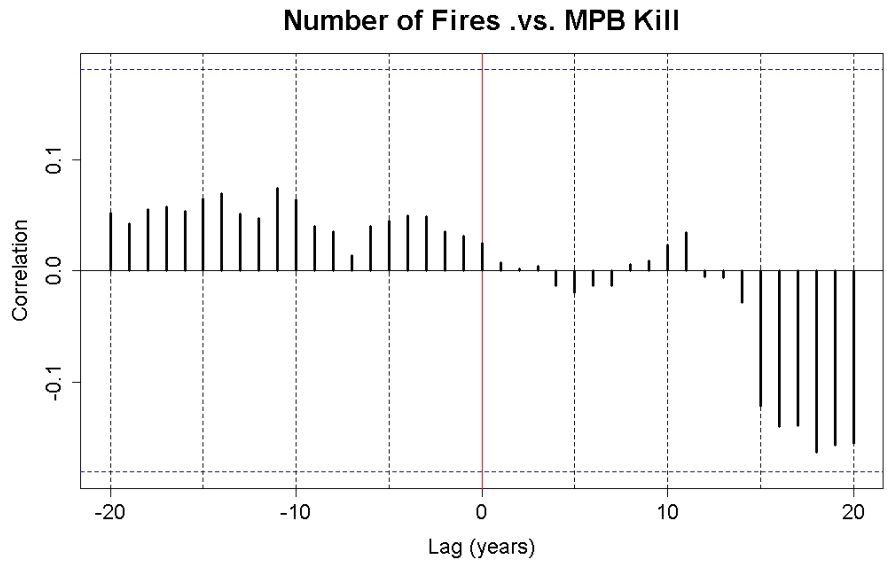

Figure 8: Cross-correlation between the number of fires in the Black Hills National Forest, and the mountain pine beetle tree-kill (MPB). Positive lags indicate that MPB leads fire occurence.

does not prove that those variables are actually the cause of the phenomenon.

To reduce the impact of correlation between timber harvest (as well as pine beetle tree kill) and known causative factors, we first modeled fire occurrence using only the two known factors, drought (as represented by the Palmer Z-index) and Spring-Summer temperature. This defines the "base" model, which is shown in figure 9. This model captures much of the year-to-year fluctuation in fire occurrence, as well as the enhanced fire risk during the 1930s (due to the severe drought of those years) and some (but not all) since 1985.

The *residuals* from this model (the difference between the observed counts and the model values) are shown in figure 10. We used these residuals to look for correlation with other variables, in the hope that the impact of known factors (drought and temperature) has mostly already been acounted for, so the true impact of other variables can be more isolated.

Cross-correlation of base-model residuals with timber harvest is shown in figure 11, and with pine beetle tree-kill in figure 12. Timber harvest still shows signficant correlation with fire occurrence with a delayed effect, peaking about 12 years after harvest. Pine beetle tree-kill still shows no sign of any correlation with fire occurrence.

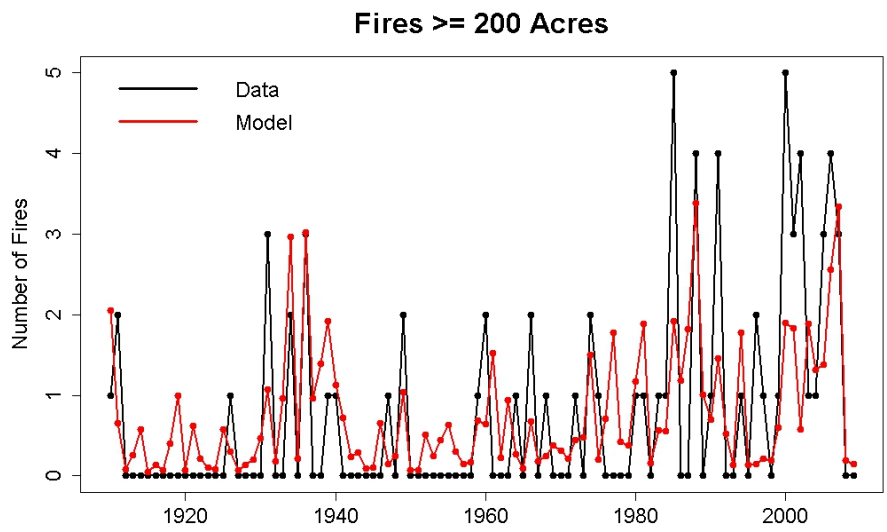

Figure 9: Model using Palmer Z-index and Spring-Summer temperature.

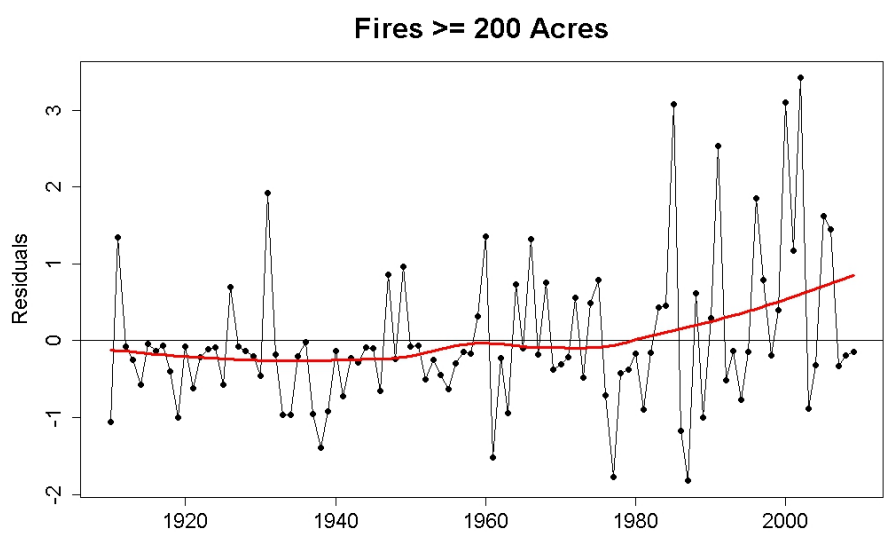

Figure 10: Residuals from a model using Palmer Z-index and Spring-Summer temperature.

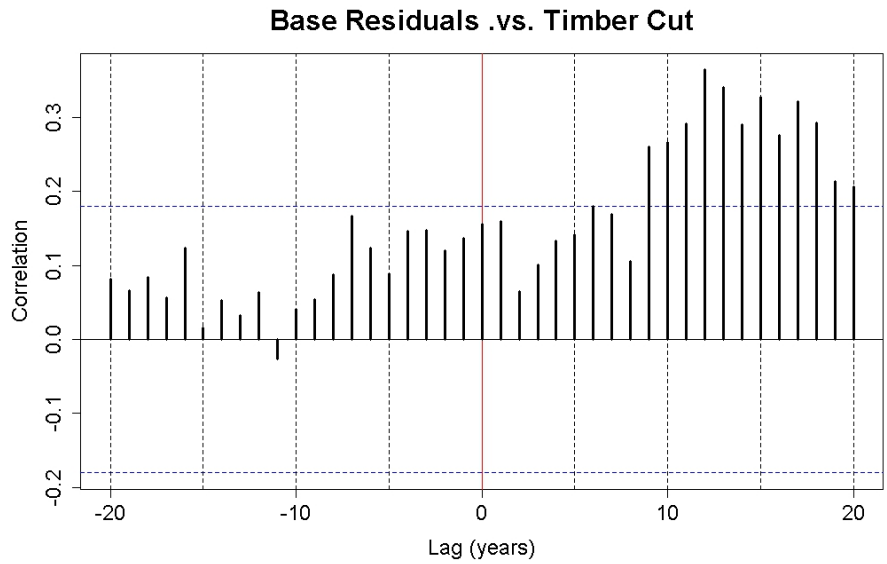

Figure 11: Cross-correlation between the residuals from the base model, and timber cut. Positive lags indicate that timber cut leads fire occurence.

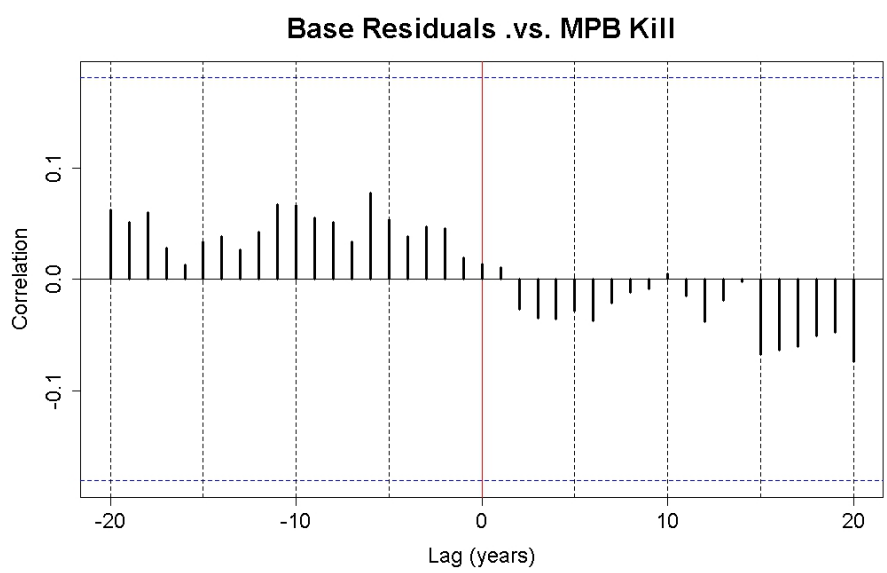

Figure 12: Cross-correlation between the residuals from the base model, and the mountain pine beetle tree-kill (MPB). Positive lags indicate that MPB leads fire occurence.

3.4 Models of the Number of Large Fires

We therefore first tested a variety of models using as predictor variables drought, Spring-Summer temperature, and a single additional variable. For the additional variable we tried both timber harvest and pine beetle tree kill, and allowed each to have a delayed effect by including a lag in its influence. All possible lags from 0 years (immediate effect) to 15 years were tested. Model quality was evaluated by AIC.[5]

The best model was one using timber harvest at lag 12, i.e., modeling the number of large fires as a function of drought, Spring-Summer temperature, and timber harvest 12 years previously. On the face of it, this would indicate that greater timber harvest increases the risk of large fires. However, we caution again that correlation is not causation, and it is possible that the timber harvest is acting as a proxy for some other factor.

In particular, the timber harvest has increased over the years, so it may act as a proxy for any long-term increasing trend. Therefore we constructed a model using drought, Spring-Summer temperature, and a simple linear time trend. This model is almost as good as the model using lag-12 timber harvest, and although AIC slightly prefers the timber-harvest model, the difference is not statistically significant. Hence statistics alone cannot decide between these two choices. Both the lag-12 timber harvest model, and the linear trend model, are shown in figure 13.

We further tested adding yet more predictor variables to the model. We tried adding a 2nd lagged value of timber harvest, a lagged value of pine beetle tree kill, and combining the lag-12 timber harvest and simple linear trend. None of these more complex models showed improvement over the simpler models. Therefore we conclude that the lag-12 timber harvest model and the linear trend model (both shown in figure 13) are the best of the models tested in this study, and the data do not significantly prefer one over the other.

3.5 Model Interpretation

It is crucially important to emphasize several aspects of the model results. First is the fact that timber cut may actually not be a causative factor in fire risk. Second is the fact that even if it is, the fact that its influence peaks at lag 12 years does *not* indicate that timber harvest "waits 12 years" before influencing fire risk. Timber harvest shows very strong *autocorrelation*, meaning that values in nearby years are strongly correlated. Therefore a

[5]The *Akaike Information Criterion*, or AIC, is a measure of the quality of a statistical model which accounts for both how well the model fits the data, and how many parameters are required to define the model [Akaike 1974].

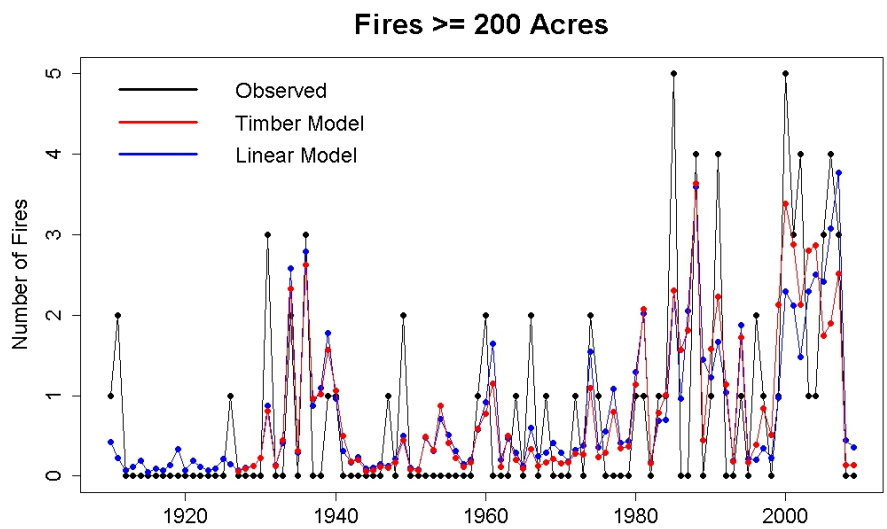

Figure 13: Models based on Palmer Z-index, Spring-Summer temperature, and a single additional variable. The blue line shows the model using a linear time trend, the red line shows the model using lag-12 timber harvest values instead.

given year's value acts, in strong measure, as a proxy for values several years before and after. If the timber harvest/fire risk association is causal, then increased fire risk has been the result of *sustained* timber harvest, and its impact is felt about a decade later.

Coefficients for the lag-12 timber harvest model are given in table 1, and for the linear trend model in table 2. In both cases, as expected, drought (negative values of the Z-index) and heat (higher Spring-Summer temperature) increase fire risk. For the timber harvest model, sustained harvesting of 100 million board-feet per year increases the expected number of fires per year in the following decade by about 2. For the linear trend model, the number of large fires per year is increasing at a rate of about 3 per century. Note that there is considerable uncertainty in these figures, with standard errors which are comparable to the expected increases.

Table 1: Coefficients of the lag-12 timber harvest model.

Variable	Coefficient	Std.Err
Palmer Z-index	-0.63	0.43
Spring-Summer Temperature	0.72	0.42
Lag-12 Timber Harvest	0.022	0.011

Table 2: Coefficients of the linear trend model.

Variable	Coefficient	Std.Err
Palmer Z-index	-0.76	0.45
Spring-Summer Temperature	0.82	0.34
Linear Trend	0.031	0.018

It is noteworthy that according to these data, there is no significant indication of a relationship between pine beetle tree kill and fire risk. In fact, although the models including pine beetle data were inferior to those excluding that factor, when it was included the *sign* of the effect was opposite to expectation, indicating that greater tree kill actually reduces the expected number of large fires. It is clear that the data are sparse (covering only one region) and contain considerable uncertainties. However, if a causal relationship were as extreme as has been often suggested, amounting to a "tinderbox primed for wildfire," then these data would have revealed it. Certainly a relationship cannot be ruled out – but just as certainly, the extremity which has been claimed in public and policy discourse *can* be ruled out.

4. Fire Size

In addition to concerns about pine beetle infestation increasing the likelihood of large fires, there is also concern about its increasing the chance of fires becoming *very* large, in particular that it increases the risk of fires escalating to become "crown fires" which burn suspended material at the canopy level, and which tend to be larger and harder to contain. Some of the concern over increase in very large fires was stated by forest supervisor John Twiss in his 2002 Congressional testimony:

> "... *the forest experienced the four largest forest fires in Black Hills's recorded history in 2000 and 2001, which burned 120,000 acres ...*"

The conclusion drawn by many is that recent changes, in particular the recent massive pine beetle infestation, have increased the likelihood of very large fires.

However, supervisor Twiss's statement is not correct. Although 2000 and 2001 did indeed have four very large fires which burned 120,000 acres, most of the burn area was due to the Jasper fire of 2000, which alone consumed over 83,000 acres. The Jasper fire was the largest in recorded history in the Black Hills, but the three next-largest fires occurred in 1931, 1939, and 1985.

Nonetheless, there has been a high number of very large fires since the increase in wildfire activity which begin in 1985. What seems not to have been addressed is whether or not the increase in very large fires is simply due to the fact that there have been more fires. To investigate this question, we divided the occurrences of large fires ($\geq$ 200 acres burned) into two time spans, before and after a "cutoff" year. We then compared the distribution of fire size of the pre- and post-cutoff data. If any factor (not just pine beetle infestation) has increased the likelihood that fires will escalate to extreme size, then there should be a difference in the distribution of fire size between the two samples.

We compared pre- and post-cutoff fire size distributions for a number of different cutoff years. This includes 1985 (the year in which the number of fires shows marked increase), 2000 (the year beginning the "second wave" of increased number of fires), and 2001 (the year in which pine beetle tree kill increased dramatically). Distributions were compared using a standard statistical test, the non-parametric Kolmogorov-Smirnov test. None of the selected cutoff years indicated a significant difference in the distribution of fire size before and after. Comparing fires before 1985 to those during and after 1985 gave a p-value of 0.45, comparing fires before 2000 to those during and after 2000 gave a p-value of 0.22, and comparing fires before 2001 to those during and after 2001 also gave a p-value of 0.22. None of these results is even remotely statistically significant.

This does not rule out the possibility that a number of factors (including pine beetle infestation) actually have influenced the chance of wildfires escalating to extreme size – lack of evidence is not evidence of a lack. But there does indeed seem to be a lack of actual *evidence* that recent wildfires are consistently larger than in preceding years. As far as the data indicate, the greater number of very large fires in recent years is simply due to the greater number of fires.

5. Recent Research on Pine Beetle Infestation and Wildfire Risk

Several recently published research papers have directly addressed the issue of the effect of pine beetle infestation on the risk of wildfire and its likely severity. Most of this research has surveyed areas which have been infested in order to conduct a census of the fuel loadings, on the surface, in the understory, and in the canopy. This information is then used in computer models which simulate the likelihood of ignition, and the likely progress of fires, under a variety of weather conditions. Risks are generally evaluated at different stages following pine beetle infestation, including the early "red" phase when dead needles are still on trees, the "gray" phase when needles have fallen to the forest floor, and the "old" phase when many dead trees have fallen and replacement foliage is well advanced. In general such studies

indicate far less risk enhancement than simple intuition would presuppose, and some indicate reduced risk, but the specific impacts on fire risk vary between studies, in part because of differences in the factors which are included in the computer models, and in part due to different results from field surveys of how infestation has affected fuel loads in infected areas.

The strongest indication of increased risk was reported by Schoennagel et al. [2012], who found that lower fuel moisture, more open canopies, and higher surface fuel load due to treefall increased risk factors in many simulations

> *Across moisture scenarios, canopy fuel moisture was one-third lower in Red and Grey stages compared to the Green stage, making active crown fire possible at lower wind speeds and less extreme moisture conditions. More-open canopies and high loads of large surface fuels due to treefall in Grey and Old-MPB stages significantly increased surface fireline intensities, facilitating active crown fire at lower wind speeds (3055 km/hr) across all moisture scenarios. Not accounting for low foliar moistures in Red and Grey stages, and large surface fuels in Grey and Old-MPB stages, underestimates the occurrence of active crown fire. Under extreme burning conditions, minimum wind speeds for active crown fire were 2535 km/hr lower for Red, Grey and Old-MPB stands compared to Green. However, if transition to crown fire occurs (outside the stand, or within the stand via ladder fuels or wind gusts 65 km/hr), active crown fire would be sustained at similar wind speeds, suggesting observed fire behavior may not be qualitatively different among MPB stages under extreme burning conditions. Overall, the risk (probability) of active crown fire appears elevated in MPB-affected stands, but the predominant fire hazard (crown fire) is similar across MPB stages and is characteristic of lodgepole pine forests where extremely dry, gusty weather conditions are key factors in determining fire behavior.*

A more moderate appraisal is found in Simmard et al. [2011], who found little difference in surface fuel load until well after infestation, and reduced canopy fuel load, and noted that thinning the canopy may reduce the chance of active crown fire.

> *Dead surface fuel loads of all size categories did not differ among undisturbed, red, and gray-stage stands. Compared to undisturbed sites, red and gray-stage sites had on average 53% lower canopy bulk density, 42% lower canopy fuel load, and 29% lower canopy*

> *moisture content, but had similar canopy base heights (3.1 m). In subsequent decades, coarse wood loads doubled and canopy base height declined to 0 m. Modeling results suggested that undisturbed, red, and gray-stage stands were unlikely to exhibit transition of surface fires to tree crowns (torching), and that the likelihood of sustaining an active crown fire (crowning) decreased from undisturbed to gray-stage stands. Simulated fire behavior was little affected by beetle disturbance when wind speed was either below 40 km/h or above 60 km/h, but at intermediate wind speeds, probability of crowning in red- and gray-stage stands was lower than in undisturbed stands, and old post-outbreak stands were predicted to have passive crown fires. Results were consistent across a range of fuel moisture scenarios. Our results suggest that mountain pine beetle outbreaks in Greater Yellowstone may reduce the probability of active crown fire in the short term by thinning lodgepole pine canopies.*

Tinker et al. [2009, summarized in Tinker et al. 2011] found reduced hazard in the early to mid stages after infestation.

> *Our data did not support the hypothesis that mountain pine beetle outbreak increased fire hazard in the short term (1 to 5 years post-outbreak). On the contrary, modeling results suggested that beetle outbreak may actually reduce the probability of active crown fire. Because canopy bulk density is the primary driver of crowning, post-outbreak reduction of canopy fuels would be the most likely mechanism that explains the reduction of fire hazard in red and gray stands. Torching Index went from 40 km/h in the undisturbed stands to about 70 km/h in the gray stands, suggesting that greater wind speeds would be needed for active crown fire to occur in theses stands. Most among-class differences in fire behavior occurred in a window of wind speed ranging from 30 to 60 km/h, where red- and gray-stage stands had lower crown fraction burned, headfire rate of spread, fireline intensity, and heat per unit area.*
>
> *It is often thought that fire hazard is extreme in the red-needle stage because dead foliage is still in the canopy but is very dry. However, canopy bulk density of red-stage stands in our study was 50% lower than in undisturbed stands, and similar to that of the gray stands, suggesting that dead needle fall may already occur in the red-needle stage. This is supported by field observations that mortality in these stands occurred over a number of years, and that all stands had a mixture of red-needle, bare, and live trees in different proportions. Thus, although canopy foliar moisture*

> *during the red-needle stage was reduced to about 78% of its pre-outbreak value, we did not observe increased torching or crowning in the fire modeling results, probably because of the overriding effect of canopy bulk density.*
>
> *In the decades that followed the infestation, the growth of understory saplings greatly reduced canopy base height, providing ladder fuels that facilitated torching. Thirty-five years after the outbreak, effective canopy base height was down to 0 m, suggesting that torching could potentially occur even in the absence of wind. Canopy bulk density however was still low and did not allow crowning, and thus only passive fires were predicted.*

In a fundamentally different kind of study, Kulakowsky and Jarvis [2011] compared burned to unburned areas rather than simulating conditions based on fuel load measurements, finding that the likelihood of fire was dominated by dry climatic conditions rather than changes in fuels from beetle infestations.

> *Outbreaks of bark beetles and drought both lead to concerns about increased fire risk, but the relative importance of these two factors is the subject of much debate. We examined how mountain pine beetle (MPB) outbreaks and drought have contributed to the fire regime of lodgepole pine forests in northwestern Colorado and adjacent areas of southern Wyoming over the past century. We used dendroecological methods to reconstruct the pre-fire history of MPB outbreaks in twenty lodgepole pine stands that had burned between 1939 and 2006 and in 20 nearby lodgepole pine stands that were otherwise similar but that had not burned. Our data represent c. 80% of all large fires that had occurred in lodgepole pine forests in this study area over the past century. We also compared Palmer Drought Severity Index (PDSI) and actual evapotranspiration (AET) values between fire years and non-fire years. Burned stands were no more likely to have been affected by outbreak prior to fires than were nearby unburned stands. However, PDSI and AET values were both lower during fire years than during non-fire years. This work indicates that climate has been more important than outbreaks to the fire regime of lodgepole pine forests in this region over the past century. Indeed, we found no detectable increase in the occurrence of high-severity fires following MPB outbreaks. Dry conditions, rather than changes in fuels associated with outbreaks, appear to be most limiting to the occurrence of severe fires in these forests.*

The influence of pine beetles on fire hazard is evidently complex, including factors which can both increase and decrease the likelihood both of fire ignition and of active crown fires. Clearly, different studies do not agree on the details of their effect. Yet many studies indicate reduced hazard, counter to intuition and public perception, especially during the early years after infestation, exactly the time when dead trees are prominently visible and public perception of increased hazard may be greatest.

6. Cause of Pine Beetle Outbreak

Pine beetle outbreak has occurred before in the Black Hills National Forest, but the modern one is part of a pattern of severe infestation which plagues much of the Western U.S., and recently the mountain pine beetle has extended its range northward into regions of Canada. This has stirred speculation that the reason for the outbreak is increasing wintertime temperature, leading to less hard freeze which is known to limit the spread of pine beetles.

Pine beetles have some defense against hard freeze, in particular natural antifreeze (predominantly glycerol, Bentz and Mullins [1999]), but the production of cryoprotectant is dependent on the life cycle so that pine beetles have different levels of cold tolerance at different times of year [Stahl et al. 2006]. In fact the pine beetle life cycle is not synchronized to definitive markers of the progress of seasons like length-of-day which controls many plant life cycles. Instead, pine beetle life cycles seem to be controlled primarily by temperature, which, through the regulation of its progress through various life stages, causes a natural synchronization with the seasons which is referred to as "adaptive seasonality" [Hicke et al. 2006].

In short, the impact of temperature on pine beetles is much more complex than simply greater mortality with greater hard freeze during winter. Nonetheless, hard freeze remains an important limiting factor for the spread of pine beetles and less hard freeze during winter has been implicated as a major factor in the recent extensive outbreak throughout the Western U.S. and Canada [Stahl et al. 2006].

We therefore examined temperature data from the Black Hills region to determine whether there has been a change which may be related to the most recent pine beetle outbreak. Monthly averages of mean temperature show that the years 2001 through 2011 have exhibited considerably less extreme cold during winter months than prior years (figure 14). It is perhaps especially interesting that the region has seen fewer very cold Januaries since about 1980 and *much* less January cold since 1998 (figure 15).

We also studied daily low temperature using daily station data. Note

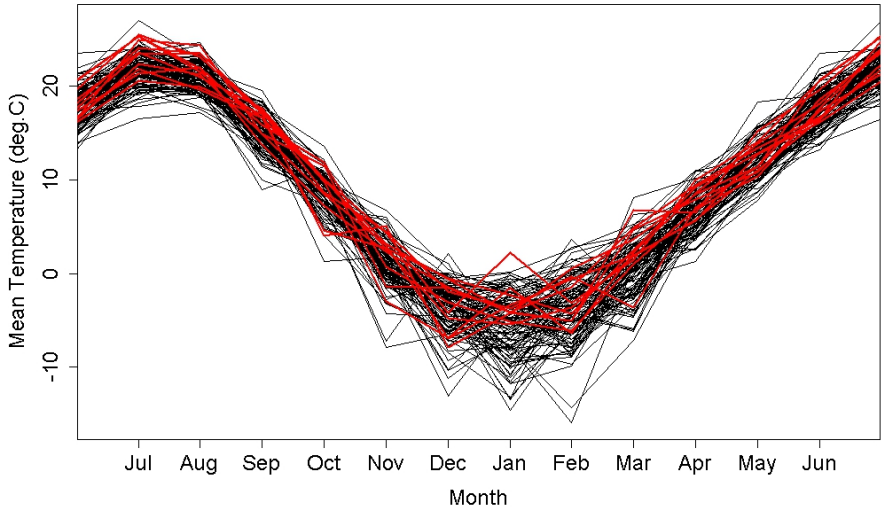

Figure 14: Monthly averages of mean temperature for the Black Hills region, using data corrected for time-of-observation bias. Years from 2001 to the present are plotted in red.

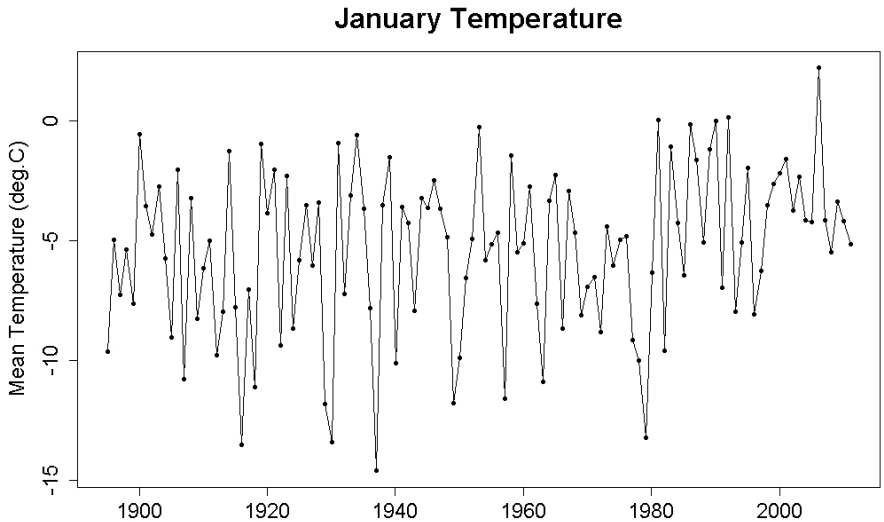

Figure 15: Monthly averages of mean temperature for the Black Hills region during the month of January, using data corrected for time-of-observation bias.

that although the monthly data for mean temperature shown in figures 14 and 15 are from the Global Historical Climate Network and are in degrees

Celsius, these are daily data from the U.S. Historical Climate Network and are in degrees Fahrenheit. Although these data are uncorrected for some climatological bias factors, they do provide direct measure of the occurrence of hard freeze by recording when temperature reached extreme low levels, and when such levels were sustained for an extended number of days.

To that end, we first transformed daily low temperature data into a measure of *persistent* overnight hard freeze, by subjecting the data to exponential smoothing on a 7-day time scale. We then noted the number of "below-zero degree days" for the smoothed low temperatures, i.e., the sum of how far each value was below zero for those days on which the value was negative. This is a clear indication of the occurrence of persistent hard freeze in the Black Hills region over time. The result is shown in figure 16. The lack of persistent hard freeze since 1998, compared to prior years, is nothing less than remarkable.

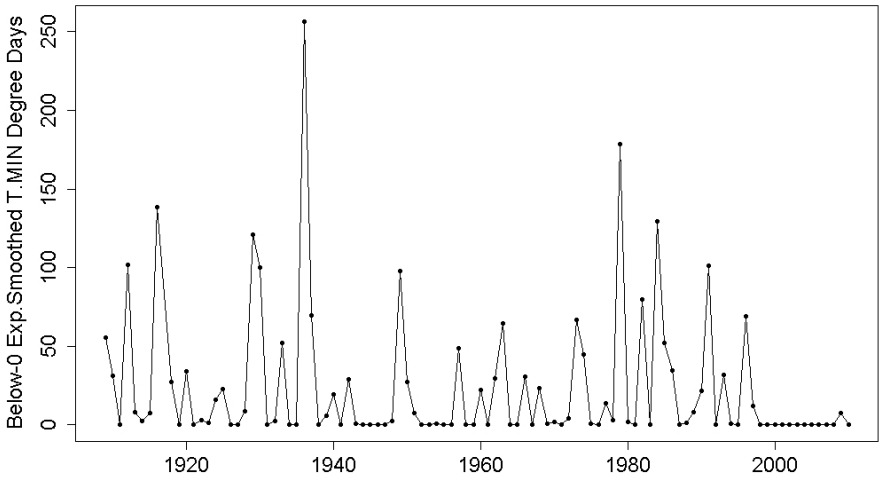

Figure 16: Below-zero degree days for exponentially smoothed overnight low temperature.

By no means does this prove that the recent infestation in the Black Hills is due to warmer wintertime temperature, in fact more than one factor is likely at play. But it is highly suggestive that warming temperature, especially the decline is sustained hard freeze during winter, is an important factor in the dramatic increase in pine beetle populations noted over much of Western North America.

7. Conclusion

The data for the Black Hills region of South Dakota shows significant increase in fire hazard in recent decades, but that increase is attributable to known causes including climate change and drought conditions, and probably also related to other factors not included in this study, such as fire suppression. While many questions remain unanswered, and fire hazard due to pine beetles cannot be ruled out, it is overwhelmingly likely that any hazard which may exist due to pine beetles is dwarfed by other factors.

Why then the extreme public fear of fire hazard due to pine beetle tree kill? An obvious reason is simple intuition, the notion that standing dead trees under any circumstances create a "tinderbox primed for wildfire" which is destined for conflagration. This intuition is shared by a number of professionals in forestry and firefighting. Yet in the specific case of mountain pine beetle infestation, the available data do not support this interpretation and much recent research actually contradicts the idea. Another is the recent increase in wildfire activity within the Black Hills National Forest. Yet this increase is not unique to the Black Hills region. Its occurrence in the mid-1980s coincides with a similar increase in wildfire activity throughout the Rocky Mountain region, at a time which is well *before* the latest pine beetle attack. Yet another is the fact that the increase in wildfires during the mid-1980s was followed by a further increase in the early 2000s, which is strongly *perceived* as coinciding with a strong increase in pine beetle infestation. However, the extreme wildfire seasons of the early 2000s commence in the year 2000 itself, which is a year *before* the dramatic increase in pine beetle tree kill observed in 2001.

It is our conclusion that there is simply no evidence to support the idea that the massive tree kill due to mountain pine beetle attack has significantly enhanced the risk of wildfire in the Black Hills National Forest. Wildfire hazard is a crucial issue which must be addressed with as clear as possible a perception of the actual risk factors. A focus on pine beetle infestation seems misplaced, threatening to draw attention away from factors which have strong and demonstrable impact on fire hazard and to divert limited resources to less productive strategies. Surely, excessive rhetoric about the urgent fire danger posed by pine beetle infestation, sometimes to the point of hysteria, does not serve the public interest.

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