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Review

Climate Change and Future Fire Regimes: Examples from California

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Abstract: Climate and weather have long been noted as playing key roles in wildfire activity, and global warming is expected to exacerbate fire impacts on natural and urban ecosystems. Predicting future fire regimes requires an understanding of how temperature and precipitation interact to control fire activity. Inevitably this requires historical analyses that relate annual burning to climate variation. Fuel structure plays a critical role in determining which climatic parameters are most influential on fire activity, and here, by focusing on the diversity of ecosystems in California, we illustrate some principles that need to be recognized in predicting future fire regimes. Spatial scale of analysis is important in that large heterogeneous landscapes may not fully capture accurate relationships between climate and fires. Within climatically homogeneous subregions, montane forested landscapes show strong relationships between annual fluctuations in temperature and precipitation with area burned; however, this is strongly seasonal dependent; e.g., winter temperatures have very little or no effect but spring and summer temperatures are critical. Climate models that predict future seasonal temperature changes are needed to improve fire regime projections. Climate does not appear to be a major determinant of fire activity on all landscapes. Lower elevations and lower latitudes show little or no increase in fire activity with hotter and drier conditions. On these landscapes climate is not usually limiting to fires but these vegetation types are ignition-limited. Moreover, because they are closely juxtaposed with human habitations, fire regimes are more strongly controlled by other direct anthropogenic impacts. Predicting future fire regimes is not rocket science; it is far more complicated than that. Climate change is not relevant to some landscapes, but where climate is relevant, the relationship will change due to direct climate effects on vegetation trajectories, as well as by feedback processes of fire effects on vegetation distribution, plus policy changes in how we manage ecosystems.

Keywords: drought; forest change; fuel moisture; global warming; management; novel ecosystems; snowpack

1. Introduction

Wildfires are globally widespread and affect both ecosystem processes and distribution patterns of flora and fauna [1–3]. Investigators have characterized burning in different ways. Here we use the term fire activity to refer to the extent of burning, necessitated by the fact that some investigators report area burned [4], others report number of fires >200 ha [5], or >400 ha [6], or >5000 ha [7], the latter three apparently as surrogates for area burned; though in California number of fires >400 ha is only moderately correlated with annual area burned ($r^2 = 0.44$, $p < 0.001$ for the years 1963–2013, [8]).

Although these studies demonstrate that the determinants of fire activity are multi-factorial, climate has long been considered to play a key role [9].

Since at least the beginning of the Holocene there has been documentation of a significant link between fires and climate [10], and drought has typically been associated with years having anomalously high area burned [11–14]. One of the earliest papers implicating potential global warming impacts on wildfires was the demonstration by Westerling et al. [6] that, since 1980, the number of moderate to large forest fires has increased in western US forests and is correlated with years having earlier snow melt, and by implication higher spring temperatures (see [5] for a somewhat expanded version). This association between high temperatures in certain seasons and extent of burning has been borne out by other historical studies in western US forests [4,15–17].

Beyond the direct effect of weather (primarily winds) during a fire event, climate primarily affects fires in two ways. Warm, dry weather during the months immediately preceding the fire season reduces *moisture content* of both live and dead fuels, increasing the likelihood of ignition and spread of fires. In contrast, high precipitation a year or two prior will increase the *volume* of herbaceous fuels, which later increases the probability of ignitions and fire spread [18]. Climate impacts on fuel moisture vs. fuel volume are of varying importance in different vegetation types.

For example, both closed canopy mixed conifer forests and ponderosa forests in the Sierra Nevada of California have high fire activity in drought years (Figure 1), indicating both fuel types respond to low fuel moisture. However, the prior year's precipitation has no relationship with fires in the mixed conifer forests, where fire spread is dependent on litter. On the other hand, prior year's precipitation is strongly correlated with fires in the more open ponderosa forests, where fire spread is dependent on dried herbaceous fuels that increase in volume during years of high rainfall. Not surprisingly, this effect of prior rainfall is generally only observed in vegetation types where fire spread is dependent on herbaceous fuels, primarily grasslands and savannas. Sometimes this effect is evident in shrublands that burn as active crown fires (i.e., fire is not spread by surface fuels), because on such landscapes fires ignite in associated herbaceous vegetation, which acts as a wick that spreads fire into dense shrublands. This relationship with prior-year rainfall is also seen in desert ecosystems where non-native grasses are now contributing to fire spread and increased occurrence of large fires [19], and in Sierra Nevada woodlands and savannas [4].

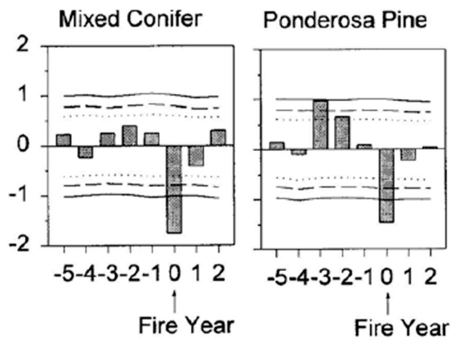


Figure 1. *y*-axis is mean June-August Palmer Drought Severity Index (positive indicates wetter than normal and negative drier than normal) in years prior and year (time 0) of a high fire activity year. The horizontal solid, dashed, and dotted lines are the 95%, 99%, and 99.9% confidence intervals, respectively, computed by Monte Carlo simulation [9].

Temperature effects on fuel moisture act by reducing moisture of live and dead fuels. Westerling et al. [6] hypothesized that high spring temperatures contributed to a more rapid melting of the snowpack, causing a longer season of drier soil conditions. Drier soils limit water uptake and thus reduce live fuel moisture, but it is not clear how drier soils per se would impact dead fuel moisture. However, higher temperatures during spring and summer, although correlated with early snow melt, will reduce moisture of both live fuels and dead surface fuels by increasing evaporative demands during the dry season. Distinguishing between these two processes is difficult with the Westerling study [6] as it reports only the timing of peak river flow in associated watersheds as a surrogate for snowpack melt-off date, and by implication spring temperature. Littell et al. [15] concluded that snowpack melt-off was important as they found a negative relationship between winter precipitation and fire activity in the Sierra Nevada and Rocky Mountains. However, Medler et al. [20] measured areal and temporal extent of snow cover in the western US and found no relationship with area burned. Keeley and Syphard [4] found a negative correlation between spring snowpack depth and area burned in Sierra Nevada forests, but doubted there was a causal relationship since the climate variables most strongly tied to snowpack melt-off were not parameters most strongly affecting area burned. They hypothesized that although high spring temperatures did result in early melt of the snowpack, fires were more strongly controlled by direct effects of spring and summer temperatures on live and dead fuel moisture. Likewise, Abatzoglou and Kolden [16] found that although early snow melt-off did correlate with higher early season fire activity, it was only weakly associated with annual area burned and suggested that temperature and precipitation within the fire season were more important determinants of area burned in western US forests.

In summary, high temperatures and drought have substantial impacts on the extent of burning in the western US, and elsewhere in the world [21,22]. There is general agreement that climate operates through effects on fuel moisture and fuel volume, and the relative importance of each varies with vegetation type. It is now widely recognized that the relationship between climate and fire activity has important implications for future climate change impacts on fire regimes. Fire response to climatic variation is shown to be correlated at some level to global circulation patterns such as the Pacific Decadal Oscillation or El Nino-Southern Oscillation [19,23]. However, here we focus on more direct and local climate drivers of fire activity.

2. Fire and Global Warming

Global warming is clearly projected by countless climate-modeling studies that support a strong relationship between a largely anthropogenically caused rise in atmospheric CO_2 and annual global temperatures. Although the rate of future temperature rise will depend on lifestyle decisions, there is a consensus that annual temperatures will increase by 3–6 °C in the 21st century [24] and will not be easily reversible [25].

What does this mean in terms of future fire regimes? Modeling results generally predict increased fire frequency and fire severity for much of the globe [26–29]; however, these projections need to be viewed with caution as they are based on rather uncertain and spatially variable relationships between temperature and fire activity, and comprise ecosystems with very different fuel structures. In general, models that predict future fire regimes depend on relationships between annual temperature and fire activity that are based on historical studies correlating annual climate variation with fire activity, and often at very different spatial scales. In addition, in order to model future regimes certain simplifying assumptions are needed, such as fires are not limited by ignitions [30], a position that a number of fire scientists find unacceptable [31,32].

Historical studies of annual variation in climate and fire have revealed several important points that need to be understood in future modeling efforts. One is that the scale of focus has profound impacts on recognizing which climate parameters are most critical to fire activity. Even for a single region such as California, the resulting relations between climate and fire are rather different dependent on the size of the subregion under consideration (Table 1).

Secondly, climate models focus on annual temperature change, yet annual variation in area burned is not strongly tied to average annual temperature, but rather to temperatures in particular seasons [4,15,16]. Understanding how this seasonal relationship plays out relative to future climate models is important to future forecasts of fire regimes.

Thirdly, there is an implicit assumption in these analyses that there is a climate signal correlated with annual fire activity on all fire-prone landscapes, yet some fail to show a significant fire-climate relationship (Table 1), and likely are controlled by more direct anthropogenic impacts such as ignition patterns.

Broad regional scale analyses of fire and climate relationships for the western US are widely reported; however, because climates vary remarkably across this landscape it is difficult with this broad brush approach to sort out spatial from temporal variation. For example, considering all western US forests collectively, as the year-to-year temperature anomalies (i.e., the difference from the long-term average) during spring and summer increases, the number of fires over 200 ha increases [17]. It is tempting to interpret this pattern as reflecting temporal patterns of temperature anomalies and their effect on fire activity. However, analyses over such broad regions often reflect as much spatial variation in climate as temporal changes. Failing to differentiate between temporal and spatial variation can have profound effects on the resulting climate model for fire activity.

Table 1. Examples of models relating annual area burned to climate parameters.

Reference	Regional Historical Divisions * Record	Region	Vegetation	r^2	Model (Strongest Variables)
[16]	GACC 1984–2010	NO (N coast/N interior)	forest	0.54	July–October fine fuel moisture
	GACC 1984–2010	NO (N coast/N interior)	non-forest	0.35	Prior year April–October T
	GACC 1984–2010	SO (sierra/C coast/S cal)	forest	0.44	May–July evapotranspiration
	GACC 1984–2010	SO (sierra/C coast/S cal)	non-forest	0.44	15 June–15 September T
[15]	Bailey 1977–2003	Sierra (& N coast)	forest/woodland	0.53	Sum ppt, prior win ppt
	Bailey 1977–2003	CA chaparral	chaparral/woodland	0.54	Prior winPDSI, sumppt, 2 prior
	Bailey 1977–2003	CA woodland	woodland/grass/chap	0.47	Sum ppt, prior win temp, spr T
[4]	NOAA/USFS 1910–1959	Sierra (C&S)	forest	0.41	Spr ppt, win ppt
	NOAA/USFS 1960–2010	Sierra (C&S)	forest	0.53	Sum T, spr ppt
	NOAA/Cal Fire 1910–1959	Sierra (C&S)	woodland/grass/chap	0.34	Prior spr ppt, spg T, sum ppt
	NOAA/Cal Fire 1960–2010	Sierra (C&S)	woodland/grass/chap	0.27	Prior spr ppt, priorwinppt, sumT
[8]	NOAA/USFS 1910–2013	Southern Calif	chaparral/woodland/forest	0.02	-
	NOAA/Cal Fire 1910–2013	Southern Calif	chaparral/grass/woodland/	0.09	

* GACC: Geographic Area Coordination Centers; NOAA: National Oceanic and Atmospheric Administration; Bailey: Bailey ecoprovinces; & Includes Sierra Nevada, central coast and southern California; $ Includes north coast and north interior California.

Using California as an example, consider US Forest Service (USFS) lands, which cover an extensive latitudinal range. Here temperatures are inversely correlated with latitude; r^2 = 0.68, 0.59, 0.69, 0.73, $p < 0.001$, for winter, spring, summer and autumn, respectively, on USFS lands in California [8]. In addition, annual area burned is inversely correlated with latitude; $r^2 = 0.15$, $p < 0.001$. Thus, before investigating temporal patterns of how fire activity varies with climate, we need to appreciate there is significant spatial variation as well as temporal variation. In our studies of fire-climate relationships in California we have investigated these relationships within climatically homogeneous divisions as defined by NOAA [33], focusing on the main fire-prone landscapes in the state. At this scale we find that fire-climate relationships are remarkably different from one climate division to another. For example, a 104 years of records reveal highly significant correlations between temperature and area burned in the Sierra Nevada (Figure 2a), but not in the southern part of the state (Figure 2b). In addition, where there are significant relationships (Figure 2a), winter and autumn temperatures are not associated with annual area burned, whereas spring and summer temperatures are.

Clearly spatial scale will greatly alter our choice of the best model for predicting future fire regimes under a changing climate. This in part accounts for the differing models in Table 1. Abatzoglou and Kolden [16] used large management units that cut across different climate regimes in California; for example, their region SO comprised such a large area that it included both the NOAA climate divisions of the Sierra Nevada and South Coast (Table 1), as well as the Central Coast, regions that have very different fire-climate relationships (Figure 2, Table 1). It is important if we are to make sound predictions about how global warming will impact fire regimes we work within climatically similar regions, e.g., the NOAA divisions shown in Table 1 as well as within similar vegetation types [4]. Indeed, Abatzolou et al. [34] contended that even a finer scale spatial resolution is needed to capture regional climate modes due to orgographic and coastal effects. There might also be a need for even finer spatial scales as mountainous landscape climates vary from one watershed to another; however, at some point this becomes counterproductive since large fires burn across broad landscapes with variable climates. In addition, we may be better served by focusing on more direct biophysical parameters such as evapotranspiration rather than temperature and precipitation as demonstrated by Abatzoglou and Kolden [16].

Spatial scale is also critically important in terms of making future fire regime projections. Indeed, in central California it appears the Sierra Nevada temperature change has been relatively unremarkable over the past century in comparison to the Central Valley [35]. Using broad regional fire-climate patterns [5,26], when it is apparent that there is marked sub-regional variation (e.g., Figure 2), may not lead to productive predictions.

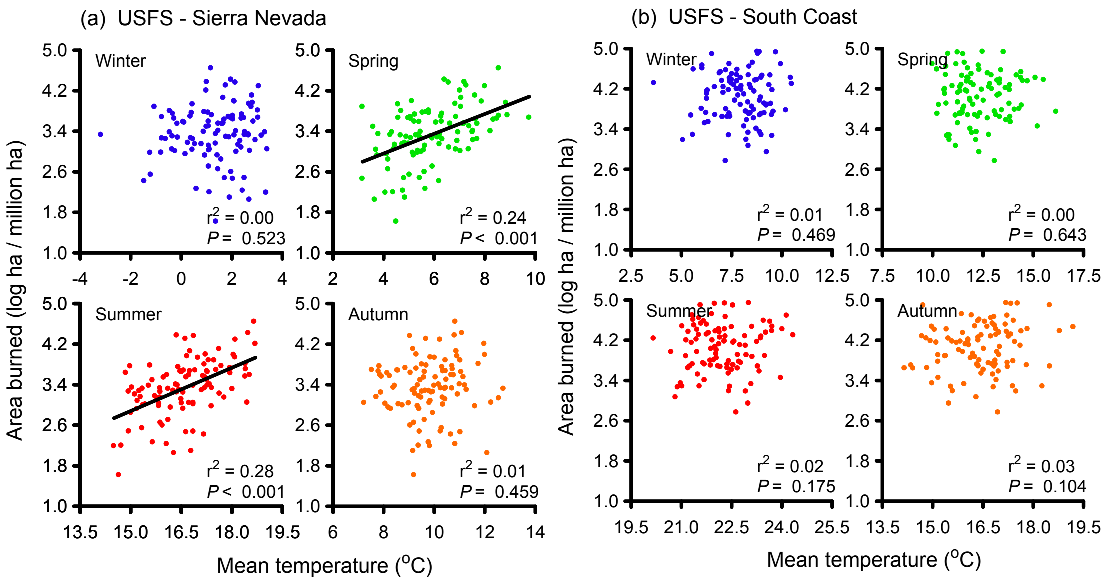


Figure 2. Seasonal mean temperature vs. annual area burned for USFS lands in two climate divisions, (**a**) Sierra Nevada and (**b**) South Coast [8].

These data support the following points: First, increasing annual temperatures in and of themselves do not predict higher fire activity, rather the effect is highly dependent on season, primarily spring and summer temperatures (Figure 2a). Secondly, it is important to focus climate-fire analyses on climatically homogeneous divisions and preferably separating montane forests from foothill savannas and shrublands, in large part because these generally have very different fuel structures that respond to different climate signals. Thirdly, not all parts of the landscape are equally sensitive to climate change. In the southern part of the state (Figure 2b), and in lower elevations (Cal Fire lands) of the Sierra Nevada [4] higher temperatures in any season are not reflected in greater fire activity. In other words, fire activity is apparently not strongly climate-limited. This is consistent with the conclusion that climate plays a larger role in dictating fire regimes in mesic than arid environments [36,37]. On these landscapes climatic conditions are suitable most years for massive wildfires (e.g., the coolest summer temperatures in the South Coast region (Figure 2b) are higher than the highest temperatures in the Sierra Neavada subregion (Figure 2a), so that other direct anthropogenic impacts may play a larger role; in other words, fire activity appears to be ignition-limited [38], which calls into question premises behind some modeling exercises. These nuances in fire-climate relationships are particularly important to consider because broad brush approaches to future fire regimes sometimes predict extraordinary increases in fire activity, e.g., [28], that may not be realistic.

3. Fire and Drought

Drought plays a key role in driving fire regimes and annual precipitation is a primary driver of drought variability [39]. In some parts of the western USA droughts have become more intense in recent decades, particularly so in southern California (Figure 3), though it is unclear if this is a trajectory for future drought. Future climate change projections of precipitation range between a 5% increase or decrease in precipitation by 2060 in California [40,41].

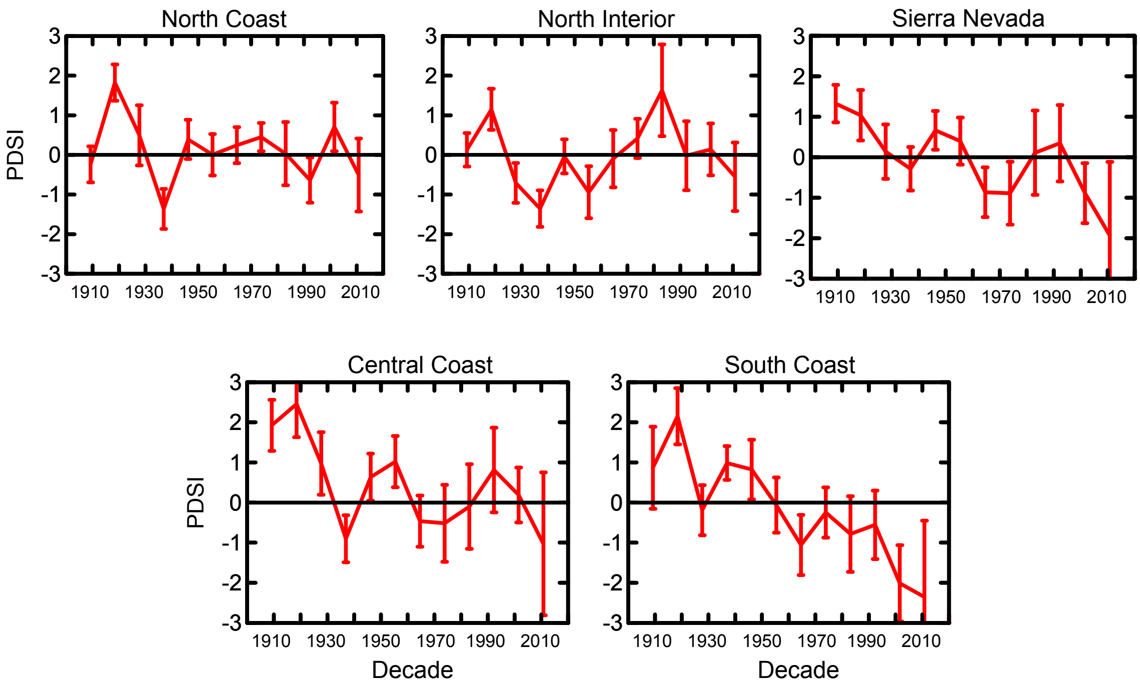


Figure 3. Decadal average (SE bars) Palmer Drought Severity Index for all months of the year for the 20th and 21st century in the NOAA climate divisions from north to south in California (http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/).

At present it is hard to distinguish current droughts from natural drought cycles, which complicates parsing out the influence of anthropogenic climate change [42]. Although natural drought cycles may dominate the current picture, it appears that anthropogenic-caused global warming is exacerbating the effects of drought; it is estimated to have contributed 5%–18% to the severity of one of the worst recent droughts in 20th-century California history [39]. This recent drought has been associated with severe die-off of *Pinus ponderosa* in mid-elevations of the Sierra Nevada (Figure 4). While we might expect future droughts on average to be more intense, it is open to debate as to whether or not droughts in the future will be worse than our worst droughts in the past.

It is unclear to what extent droughts, which may not be the result of anthropogenic warming, may have contributed to increased temperatures in recent decades. Droughts are associated with decreased cloud cover, which contributes to elevated temperatures [43]. This is not a recent global warming phenomenon as in California over the past 100 years there has been a negative relationship between spring temperatures and spring precipitation (r^2 = 0.28, p < 0.001) [8]. Thus, a recent trajectory of increased temperature may not be solely led by anthropogenically driven warming. This of course is not meant to downplay the importance of global warming, only to illustrate one more complexity in determining the appropriate fire-climate model for any given region (e.g., Table 1).

Another consideration is that, even if precipitation does not decline in the future, increased temperatures may exacerbate water deficit, and thus evaporative demand and plant water stress, which has been linked to forest mortality [44,45], and thus altered fuel conditions, as well as possibly the impact of fire severity [46]. Potential evapotranspiration will likely play a significant role in modeling future drought impacts [47].

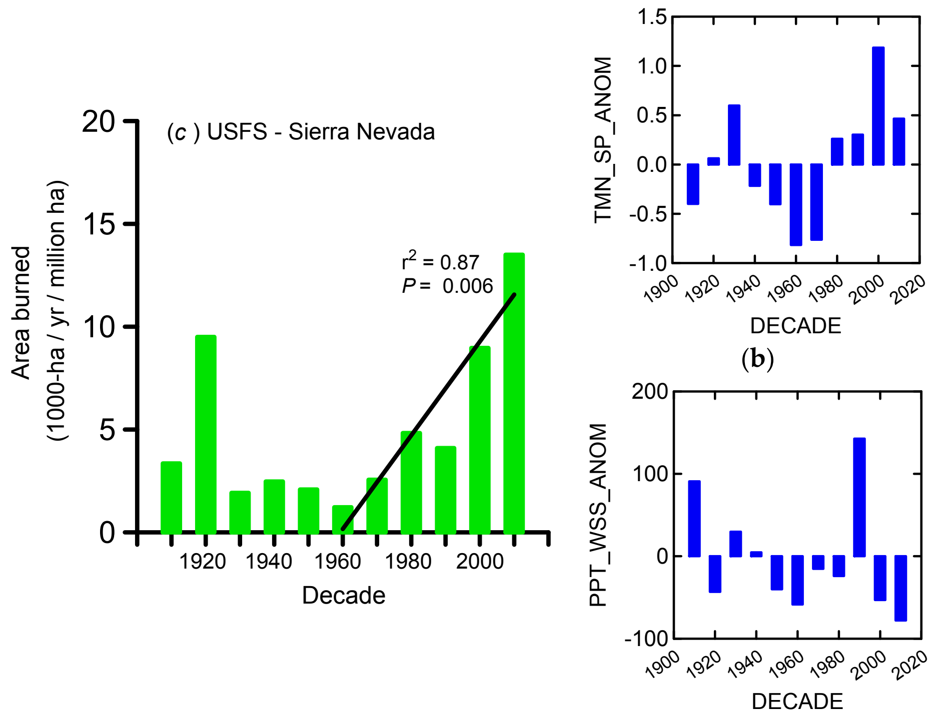
Figure 4. Severe die-off of *Pinus ponderosa* in a mixed conifer forest on the north-facing slope of Case Mountain in the southern Sierra Nevada Range, California, in July 2016 (lower slope dominated by chaparral that experienced little or no die-off). This followed a near-record-breaking drought during 2012–2014, which is thought to have been exacerbated by anthropogenic warming both directly due to physiological stress and indirectly through enhanced pathogen activity. Parsing out the role of global warming is complicated by the fact that these forests have substantially higher tree density due to 125 years of fire suppression, a perturbation to the natural regime of fires every 10–20 years (photo by Jon E. Keeley).

4. Fire–Climate Interaction Is a Moving Target

One of the complications in making forecasts of future fire regimes is that the nature of fire-climate relationships can change over time. Forests in both the Sierra Nevada of California [4] and the northern Rocky Mountains [48] have very strong fire-climate relationships that span the 20th and 21st centuries. Of particular interest is the fact that the climate parameters driving high fire activity in the early 20th century are not always those driving current fire activity. For example, in Sierra Nevada forests from 1910 to 1959 the strongest variable controlling area burned was spring precipitation followed by winter precipitation ($r^2 = 0.41$, $p < 0.001$) [4]. However, from 1960 to 2010, mean summer temperature was the strongest variable followed by spring precipitation ($r^2 = 0.53$, $p < 0.001$). Recently we expanded this analysis from 1960 to 2013 (to include the massive Rim Fire that burned into Yosemite National Park), subsequently predicting area burned by spring temperature followed by summer temperature ($r^2 = 0.52$, $p < 0.001$) [8].

Another way of looking at this is to examine decadal patterns of burning and the associated temperature and precipitation anomalies. On USFS lands in the Sierra Nevada there were peaks in fire activity in 1920 and in 2000 and the first half of the 2010 decade (Figure 5a). While the recent peaks in fire activity are associated with positive anomalies in spring temperature, the 1920s peak was not (Figure 5b). On the other hand, there was a deficit in precipitation for all peaks in fire activity (Figure 5c).

These patterns are consistent with global warming expectations, but it also raises the possibility that future fire-climate relationships may change as well. Models of future fire regimes based on past fire-climate relationships may have limited predictive capacity. Of course it is appreciated that model development has to start somewhere and thus rudimentary modeling efforts have value in the development of a sound modeling framework; however, at the present time, such models may not be ready for directing future management decisions on fire-prone landscapes.



(**a**) (**c**)

Figure 5. (**a**) Area burned on USFS lands in the Sierra Nevada by decade; (**b**) spring temperature anomalies (i.e., the difference from the long-term average); and (**c**) annual precipitation anomalies (based on dataset in [4]).

A further complication is that, while most predictions about future fire regimes are conditioned on relationships observed in the past, there will likely be novel combinations of temperature and precipitation, varying across different temporal and spatial scales, that have no analog in the past [49,50]. Predictions of climatic impacts to future fire regimes will need to account for these types of conditions that have no historical precedent. In addition, there is reason to believe that future impacts are dependent on the order, timing and magnitude of many contingencies [51]. This suggests that statistical models may be insufficient to guide future predictions and more mechanistic models will be required.

5. Confounding Factors Affecting Future Fire Regimes

5.1. Interactions between Vegetation Trajectories and Fire Regime

Illustrative of potential interactions between climate and fire are modeling results that show forest fire severity is likely to decrease in the future due to direct climate effects on vegetation change [52]. Models incorporate climate-induced changes in vegetation type, fuel load and fire frequency and suggest a potential reduction in fire severity. As climate changes, widespread vegetation change is likely to result both independently (e.g., [53,54]), and as a result of fire-climate interactions [55]. Regardless of the driving mechanism, large-scale vegetation changes will inevitably feed back to fire regimes in complex and potentially unpredictable ways [56]. For example, the relationship between fuel structure and climatic gradients in Mediterranean regions may be more important in driving fire activity than climate variability alone [36]. As fire is inherently fuel-modulated, both in terms of volume and moisture, shorter-term increases in fire activity may ultimately drive subsequent decreases in fire simply due to biomass consumption and alterations of fuel patterns. Models developed by Liu and Wimberly [29] predict that projected vegetation change in the western US will amplify climate-driven increases in fire frequency and area burned. As such, fire-climate relationships may become increasingly unpredictable as time passes, especially because these factors will also interact with other global change drivers [57].

Some types of dynamic vegetation and fire simulation models may be useful in projecting a range of plausible future outcomes given different hypothetical interactions among fire, climate, and vegetation [58–60]. Because these models integrate empirically driven parameters and equations for mechanistic processes related to fire behavior, vegetation growth and distribution, ecosystem productivity, and climatic conditions, they may be capable of estimating potential futures based on simulated interactions among these factors, although the inherent stochasticity in these systems must be accounted for, as well as their scale of analysis.

Further complicating predictions is that global warming is occurring along with other global changes that also affect plant growth; rising CO_2 concentration, N deposition and the interaction of all of these with pests and pathogens [61]. Plants shift their optimum temperature for photosynthesis in the presence of elevated CO_2, which increases productivity. Elevated CO_2, the root cause of global warming, also increases water use efficiency, thus increasing effective precipitation, potentially offsetting the effects of warming [36,62]. Nevertheless, the extent to which CO_2 fertilization will actually affect net primary productivity remains highly uncertain [63]. Understanding and incorporating these direct physiological effects will alter future predictions about vegetation shifts, and how this will play out in terms of future fire regimes.

One important challenge to the predictive ability of models that forecast future vegetation shifts is the likelihood of ecosystem novelty, changes in species composition, nutrient cycling, and fire regimes, relative to the historical baseline [64,65].

5.2. Population Growth and Future Fires

In addition to changes in fuel volume and fuel condition, future fire regimes may also change in response to changes in ignitions, and potential increases in human ignitions will complicate parsing out the role of climate change [66]. Changes in human demography are likely to have huge impacts, not only on future fires but on their impacts to human welfare [63,67]. In recent years we have seen previously unknown levels of losses in property and lives due to wildfires in the Western US. Some of this has been attributed to climate change; however, one cannot ignore the important role of urban sprawl that has placed homes at risk by juxtaposing them with highly flammable watersheds [30,68–70]. In addition, expansion of the urban environment into wildland areas increases fire hazard because humans are a major source of fire ignitions.

Throughout much of the western US, and southern California in particular, humans play a major role in the timing and spatial distribution of fire ignitions. In southern California, humans account for >95% of all fires and, by the middle of the 21st century, it is expected that human populations will increase by 50% over current levels [31,38] This is of more concern when one recognizes that all previous predictions of future population size have undershot those increases substantially. In the southern part of the state, and at lower elevations throughout California, climate signals associated with high fire years are largely lacking (Figure 2b), suggesting that more direct human impacts control annual fire activity. On these landscapes, the potential for a large fire year exists during most years (i.e., they are not climate-limited); catastrophic fires are ignition-limited, dependent largely on the timing and spatial distribution of anthropogenic ignitions [4,71].

Not only do humans have the capacity to increase fires over natural levels, they have the capacity to change the timing of wildfires. For example, in southern California, the peak season for lightning-ignited fires is summer, whereas the worst fire weather is during the autumnal Santa Ana winds. Historically, much of this landscape likely burned when summer lightning ignitions carried over until the autumn winds, but today humans have almost certainly increased the frequency of such fire events by arsons intent on igniting fires during Santa Ana wind events. In addition, due to urban sprawl, population centers are spreading eastward, which means ignitions are more likely in the interior regions. Because the most extreme fire weather conditions are due to offshore winds, the further east the ignitions occur, the greater the potential for larger fires. Such impacts of human ignitions are already being experienced in other parts of the western US as well.

5.3. Effects of Changing Management Tactics

Fire management practices account for some unexplained variation in historical fire activity. Clearly fire suppression has reduced fires in western forests during the 20th century [72], and fuel accumulation from fire suppression has been invoked as a reason for increases in forest area burned in the last few decades [6,23,73]. Prescription burning not only can play an important role in preventing unwanted changes in fire regimes, but thinning the forest may become increasingly important as a means of reducing drought impacts on tree mortality [74].

A confounding issue is a change in fire management tactics [75]. The late-20th century increase in fire activity observed on USFS lands across the western USA began at a time of change in USFS policy [76]. In the 1960s, it was gradually being accepted that there was a natural role for fire in western forests and in order to capitalize on this resource benefit from fire, the so-called "10 am policy" was replaced with a policy of "constrain and contain." The former policy mandated aggressive action towards immediate suppression of all fires with the goal of having the fire extinguished by 10 am the following morning, but was replaced by a policy that allowed fires to burn larger areas, constrained within individual watersheds. Throughout the western USA, area burned has increased over the past several decades in most USFS forests and this may be in part due to policy change. This change in management also has been invoked to explain changes in fire activity in other parts of the world [77]. Consistent with this model is the fact that Cal Fire has retained the aggressive "10 am policy" to the present and has not experienced a 20th-century increase in fire activity on much of their state responsibility areas.

6. Conclusions

Anyone who says they have a grasp on how climate change will impact future fire regimes possesses an impressive level of optimism. It is doubtful that anyone in the early 20th century could have predicted future fire regimes and the same applies to the early 21st century. We now have a much improved grasp on the relative importance of climate across different ecosystems. Montane forested ecosystems far removed from direct human impact have historically been affected by climate much more so than lower elevation non-forested ecosystems. However, projecting future fire regimes requires a focus on expected seasonal changes in temperature. Regional analyses of fire climate relationships potentially mix sub-regions with different climate drivers and this may produce misleading forecasts of future fire regimes. In contrast to montane landscapes, in lower elevations and lower latitudes, fires are not strongly climate-limited but are ignition-limited, and on these landscapes increased population growth may ultimately be a more important factor driving future fire regimes than climate.

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References

1. Bond, W.J.; Woodward, F.I.; Midgley, G.F. The global distribution of ecosystems in a world without fire. *New Phytol.* **2005**, *165*, 525–538. [CrossRef] [PubMed]
2. Krawchuk, M.A.; Moritz, M.A.; Parisien, M-A.; Van Dorn, J.; Hayhoe, K. Global pyrogeography: The current and future distribution of wildfire. *PLoS ONE* **2009**, *4*, e5102. [CrossRef] [PubMed]
3. Van Mantgem, E.F.; Keeley, J.E.; Witter, M. Faunal responses to fire in California chaparral and sage scrub in California, USA. *Fire Ecol.* **2015**, *11*, 128–148.
4. Keeley, J.E.; Syphard, A.D. Different fire-climate relationships on forested and non-forested landscapes in the Sierra Nevada ecoregion. *Int. J. Wildland Fire* **2015**, *24*, 27–36. [CrossRef]
5. Westerling, A.L. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philophical Trans. R. Soc. B* **2016**, *371*. [CrossRef] [PubMed]
6. Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* **2006**, *313*, 940–943. [CrossRef] [PubMed]
7. Barbero, R.; Abatzoglou, J.T.; Larkin, N.K.; Kolden, C.A.; Stocks, B. Climate change presents increased potential for very large fires in the contiguous United States. *Int.J. Wildland Fire* **2015**, *24*, 892–899. [CrossRef]
8. Keeley, J.E.; Syphard, A.D. Historical fire-climate patterns in California climate divisions. *Int. J. Wildland Fire Rev.* **2016**. under review.
9. Swetnam, T.W.; Betancourt, J.L. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *J. Clim.* **1998**, *11*, 3128–3147. [CrossRef]
10. Power, M.J.; Marlon, J.; Ortiz, N.; Bartlein, N.J.; Harrison, S.P.; Mayle, F.E.; Ballouche, A.; Bradshaw, R.H.W.; Carcaillet, C.; Cordova, C. Changes in fire regimes since the Last Glacial Maximum: An assessment based on a global synthesis and analysis of charcoal data. *Clim. Dyn.* **2008**, *30*, 887–907. [CrossRef]
11. Taylor, A.H.; Beaty, R.M. Climatic influences on fire regiems in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *J. Biogeogr.* **2005**, *32*, 425–438. [CrossRef]
12. Collins, B.M.; Omi, P.N.; Chapman, P.L. Regional relationships between climate and wildfire-burned area in the Interior west, USA. *Can. J. For. Res.* **2006**, *36*, 699–709. [CrossRef]
13. Swetnam, T.W.; Anderson, R.S. Fire climatology in the western United States: introduction to special issue. *Int. J. Wildland Fire* **2008**, *17*, 1–7. [CrossRef]
14. Littell, J.S.; Peterson, D.L.; Riley, K.L.; Liu, Y.; Luce, C.H. A review of the relationships between drought and forest fire in the United States. *Glob. Chang. Biol.* **2016**. [CrossRef] [PubMed]
15. Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A.L. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecol. Appl.* **2009**, *19*, 1003–1021. [CrossRef] [PubMed]
16. Abatzoglou, J.T.; Kolden, C.A. Relationships between climate and macroscale area burned in the western United States. *Int. J. Wildland Fire* **2013**, *22*, 1003–1020. [CrossRef]
17. Westerling, A.; Brown, T.; Schoennagel, T.; Swetnam, T.; Turner, M.; Veblen, T. *Briefing: Climate and Wildfire in Western U.S. Forests*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Logan, UT, USA, 2014; pp. 81–102.
18. Westerling, A.L.; Gershunov, A.; Cayan, D.R.; Barnett, T.P. Long lead statistical forecasts of area burned in western U.S. wildfires by ecosystems province. *Int. J. Wildland Fire* **2002**, *11*, 257–266. [CrossRef]
19. Crimmins, M.A.; Comrie, A.C. Interactions between antecedent climate and wildfire variability across south-eastern Arizona. *Int. J. Wildland Fire* **2011**, *13*, 455–466. [CrossRef]
20. Medler, M.J.; Montesano, P.; Robinson, D. Examining the relationship between snowfall and wildfire patterns in the western United States. *Phys. Geogr.* **2002**, *23*, 335–342. [CrossRef]
21. Moritz, M.A.; Parisien, M-A.; Batllorei, E.; Krawchuk, M.A.; Van Dorn, J.; Ganz, D.J.; Hayhoe, K. Climate change and disruptions to global fire activity. *Ecosphere* **2012**, *3*, 49. [CrossRef]
22. Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H.; Holden, Z.A.; Brown, T.J.; Williamson, G.J.; Bowman, M.J.S. Climate-induced variations in global wildfire danger from 1979–2013. *Nat. Commun.* **2015**. [CrossRef] [PubMed]
23. McKenzie, D.; Gedalof, Z.; Peterson, D.L.; Mote, P. Climatic change, wildfire, and conservation. *Conserv. Biol.* **2004**, *18*, 890–902. [CrossRef]

24. Flato, F.; Marotzke, J.; Abiodun, B.; Braconnot, P.; Chou, S.C.; Collins, W.; Driouech, F.; Emori, S.; Eyring, V.; Forest, C.; et al. Evaluation of climate models. In *Climate Change 2013: The Physical Science Basis*; IPCC Working Group I Contribution to AR5; Cambridge University Press: Cambridge, UK, 2013.
25. Solomon, S.; Plattner, G.-K.; Knutti, R.; Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 1704–1709. [CrossRef] [PubMed]
26. Flannigan, M.D.; Krawchuk, M.A.; de Groot, W.J.; Wotton, B.M.; Gowman, L.M. Implications of changing climate for global wildland fire. *Int. J. Wildland Fire* **2009**, *18*, 483–507. [CrossRef]
27. Batllori, E.; Parisien, M.A.; Krawchuk, M.A.; Moritz, M.A. Climate change-induced shifts in fire for Mediterranean ecosystems. *Glob. Ecol. Beogeogr.* **2013**, *22*, 1118–1129. [CrossRef]
28. Yue, X.; Mickley, L.J.; Logan, J.A. Projection of wildfire activity in southern California in the mid-twenty-first century. *Clim. Dyn.* **2014**, *43*, 1973–1991. [CrossRef] [PubMed]
29. Liu, Z.; Wimberly, M.C. Direct and indirect effects of climate change on projected future fire regimes in the western United States. *Sci. Total Environ.* **2016**, *542*, 65–75. [CrossRef] [PubMed]
30. Moritz, M.A.; Knowles, S.G. Coexisting with wildfire. *Am. Sci.* **2016**, *104*, 220. [CrossRef]
31. Keeley, J.E.; Safford, H.D. Fire as an ecosystem process. In *Ecosystems of California*; Mooney, H., Zavaleta, E., Eds.; University of California Press: Oakland, CA, USA, 2016; pp. 27–45.
32. Peterson, D.L.; (U.S. Forest Service and University of Washington, Seattle, WA, USA). Personal communication, 2016.
33. National Climatic Data Center (NCDC) California Climate Divisions. Available online: https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php (accessed on 15 August 2016).
34. Abatzoglou, J.T.; Redmond, K.T.; Edwards, L.M. Classification of regional climate variability in the State of California. *J. Appl. Meteorol. Climatol.* **2009**, *48*, 1527–1541. [CrossRef]
35. Christy, J.R.; Norris, W.B.; Redmond, K.; Gallo, K.P. Methodology and results of calculating central California surface temperature trends: Evidence of human-induced climate change? *J. Clim.* **2006**, *19*, 548–563. [CrossRef]
36. Pausas, J.G.; Paula, S. Fuel shapes the fire-climate relationship: evidence from Mediterranean ecosystems. *Glob. Ecol. Biogeogr.* **2012**, *21*, 1074–1082. [CrossRef]
37. Steel, Z.L.; Safford, H.D.; Viers, J.H. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **2015**, *6*. [CrossRef]
38. Keeley, J.E.; Syphard, A.D. South coast bioregion. In *Fire in California's Ecosystems*, 2nd ed.; Van Wagtendonk, J., Ed.; University of California Press: Oakland, CA, USA, 2016; in press.
39. Williams, A.P.; Seager, R.; Abatzoglou, J.T.; Cook, B.I.; Smerdon, J.E.; Cook, E.R. Contribution of anthropogenic warming to California drought during 2012–2014. *Geophys. Res. Lett.* **2015**, *42*. [CrossRef]
40. Pierce, D.W.; Cayan, D.R.; Das, T.; Maurer, E.P.; Miller, N.L.; Bao, Y.; Kanamitsu, M.; Yoshimura, K.; Snyder, M.A.; Sloan, L.C.; et al. The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in California. *J. Clim.* **2013**, *26*, 5879–5896. [CrossRef]
41. Neelin, J.D.; Langenbrunner, B.; Meyerson, J.E.; Hall, A.; Berg, H. California winter precipitation change under global warming in the coupled model intercomparison project phase 5 ensemble. *J. Clim.* **2013**, *26*, 6238–6256. [CrossRef]
42. Fellows, A.W.; Goulden, M.L. Rapid vegetation redistribution in southern California during the early 2000s drought. *J. Geophys. Res.* **2012**, *117*, G03025. [CrossRef]
43. Iacobellis, S.F.; Cayan, D.R. The variability of California summertime marine stratus: Impacts on surface air temperatures. *J. Geophys. Res. Atmos.* **2013**, *118*, 9105–9122. [CrossRef]
44. Allen, C.D.; Breshears, D.D.; McDowell, N.G. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **2015**, *6*, 1–55. [CrossRef]
45. Overpeck, J.T. Climate science: The challenge of hot drought. *Nature* **2013**, *503*, 350–351. [CrossRef] [PubMed]
46. Van Mantgem, P.J.; Nesmith, J.C.B.; Keifer, M.B.; Knapp, E.E.; Flint, A.; Flint, L. Climatic stress increases forest fire severity across the western United States. *Ecol. Lett.* **2013**, *16*, 1151–1156. [CrossRef] [PubMed]
47. Ficklin, D.L.; Abatzoglou, J.T.; Robeson, S.M.; Dufficy, A. The influence of climate model biases on projections of aridity and drought. *J. Clim.* **2016**, *29*, 1269–1285. [CrossRef]
48. Higuera, P.E.; Abatzoglou, J.T.; Littell, J.S.; Morgan, P. The changing strength and nature of fire-climate relationships in the northern Rocky Mountains, USA, 1902–2008. *PLoS ONE* **2015**, *10*, e0127563. [CrossRef] [PubMed]

49. Williams, J.W.; Jackson, S.T. Novel climates, no-analog communities, and ecological surprises. *Front. Ecol. Environ.* **2007**, *5*, 475–482. [CrossRef]
50. Williams, J.W.; Jackson, S.T.; Kutzbach, J.E. Projected distributions of novel and disappearing climates by 2100 AD. *Proc. Natl. Acad. Sci. USA* **2006**, *104*, 5738–5742. [CrossRef] [PubMed]
51. Dugan, A.J.; Baker, W.L. Sequentially contingent fires, droughts and pluvials structured a historical dry forest landscape and suggest future contingencies. *J. Veg. Sci.* **2015**, *26*, 297–710. [CrossRef]
52. Parks, S.A.; Miller, C.; Abatzoglou, J.T.; Holsinger, L.M.; Parisien, M-A.; Dobrowski, S.Z. How will climate change affect wildland fire severity in the western US? *Environ. Res. Lett.* **2016**, *11*, 035002. [CrossRef]
53. Stephenson, N.L. Climatic control of vegetation distribution: The role of the water balance. *Am. Nat.* **1990**, *135*, 649–670. [CrossRef]
54. Franklin, J.; Serra-Diaz, J.M.; Syphard, A.D.; Regan, H.M. Global change and terrestrial plant community dynamics. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 3725–3734. [CrossRef] [PubMed]
55. Lenihan, J.M.; Drapek, R.; Bachelet, D.; Neilson, R.P. Climate change effects on vegetation distribution, carbon, and fire in California. *Ecol. Appl.* **2003**, *13*, 1667–1681. [CrossRef]
56. Bowman, D.M.J.S.; Balch, J.K.; Artaxo, P.; Bond, W.J.; Carlson, J.M.; Cochrane, M.A.; D'Antonio, C.M.; DeFries, R.S.; Doyle, J.C.; Harrison, S.P.; et al. Fire in the earth system. *Science* **2009**, *324*, 481–484. [CrossRef] [PubMed]
57. McKenzie, D.; Littell, J.S. Climate change and the eco-hydrology of fire: will area burned increase in a warming western U.S.? *Ecol. Appli.* **2016**, *26*. in press.
58. Sturtevant, B.R.; Scheller, R.M.; Miranda, B.R.; Shinneman, D.; Syphard, A.D. Simulating dynamic and mixed-severity fire regimes: A process-based fire extension for LANDIS-II. *Ecol. Model.* **2009**, *220*, 3380–3393. [CrossRef]
59. *Global. Vegetation Dynamics: Concepts and Applications in MC1 Model*; Bachelet, D., Turner, D., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2010.
60. Keane, R.E.; McKenzie, D.; Falk, D.A.; Smithwick, E.A.H.; Miller, C.; Kellogg, L.-K.B. Representing climate, disturbance, and vegetation interactions in landscape models. *Ecol. Model.* **2015**, *309*, 33–47. [CrossRef]
61. Loehle, C.; Idso, C.; Wigley, T.B. Physiological and ecological factors influencing recent trends in United States forest health responses to climate change. *For. Ecol. Manag.* **2016**, *363*, 179–189. [CrossRef]
62. Charney, N.D.; Babst, F.; Poulter, B.; Record, S.; Trouet, V.M.; Frank, D.; Enquist, B.J.; Evans, M.E.K. Observed forest sensitivity to climate implies large changes in 21st century North American forest growth. *Ecol. Lett.* **2016**. [CrossRef] [PubMed]
63. Smith, W.; Kolby, S.C.; Cleveland, C.C.; Ballantyne, A.P.; Anderegg, W.R.L.; Wieder, W.R.; Liu, Y.Y.; Running, S.W. Large divergence of satellite and Earth system model estimates of global terrestrial CO_2 fertilization. *Nat. Clim. Chang.* **2015**, *6*, 306–310. [CrossRef]
64. Moritz, M.A.; Batllori, E.; Bradstock, R.A.; Gill, A.M.; Handmer, J.; Hessburg, P.F.; Leonard, J.; McCaffrey, S.; Odion, D.C.; Schoennagel, T.; et al. Learning to coexist with wilfire. *Nature* **2014**, *515*, 58–66. [CrossRef] [PubMed]
65. Radeloff, V.C.; Williams, J.W.; Bateman, B.L.; Burke, K.D.; Carter, S.K.; Childress, E.S.; Cromwell, K.J.; Gratton, C.; Hasley, A.O.; Kraemer, B.M.; et al. The rise of novelty in ecosystems. *Ecol. Appl.* **2015**, *25*, 2051–2068. [CrossRef] [PubMed]
66. Hessl, A.E. Pathways for climate change effects on fire: Models, data, and uncertainties. *Prog. Phys. Geogr.* **2011**, *35*, 393–407. [CrossRef]
67. Mann, M.L.; Batlori, E.; Moritz, M.A.; Waller, E.K.; Berck, P.; Flint, A.L.; Flint, L.E.; Dojfi, E. Fire probability models: effects of human activity and climate change on fire activity in California. *PLoS ONE* **2016**. [CrossRef] [PubMed]
68. Gude, P.; Rasker, R.; Van den Noort, J. Potential for future development on fire-prone lands. *J. For.* **2008**, *106*, 198–205.
69. Syphard, A.D.; Keeley, J.E. Location, timing and extent of wildfire vary by cause of ignition. *Int. J. Wildland Fire* **2015**, *24*, 37–47. [CrossRef]
70. Hawbaker, T.J.; Radeloff, V.C.; Stewart, S.I.; Hammer, R.B.; Keuler, N.S.; Clayton, M.K. Human and biophysical influences on fire occurrence in the United States. *Ecol. Appl.* **2013**, *23*, 565–582. [CrossRef] [PubMed]

71. Faivre, N.; Jin, Y.; Goulden, M.L.; Randerson, J.T. Controls on the spatial pattern of wildfire ignitions in southern California. *Int. J. Wildland Fire* **2014**, *23*, 799–811. [CrossRef]
72. Fule, P.Z.; Yocom, L.L.; Montano, C.C.; Falk, D.A.; Cerano, J.; Villanueva-Diaz, J. Testing a pyroclimatic hypothesis on the Mexico-United States border. *Ecology* **2012**, *93*, 1830–1840. [CrossRef] [PubMed]
73. Hurteau, M.D.; Bradford, J.B.; Fule, P.Z.; Taylor, A.H.; Martin, K.L. Climate change, fire management, and ecological services in the southwestern US. *For. Ecol. Manag.* **2014**, *327*, 280–289. [CrossRef]
74. Van Mantgem, P.J.; Caprio, A.C.; Stephenson, N.L.; Das, A.J. Does prescribed fire promote resistance to drought in low elevation forests of the Sierra Nevada, California, USA? *Fire Ecol.* **2016**, *12*, 13–25.
75. Miller, J.D.; Skinner, C.N.; Safford, H.D.; Knapp, E.E.; Ramirez, C.M. Trends and causes of severity, size and number of fires in northwestern California, USA. *Ecol. Appl.* **2012**, *22*, 184–203. [CrossRef] [PubMed]
76. Cermak, R.W. *Fire in Forest; A History Forest Fire Control on National Forests in California, 1898–1956*; USDA Forest Service, Pacific Southwest Region: Albany, CA, USA, 2005.
77. Brotons, L.; Aquilue, N.; de Caceres, M.; Fortin, M.-J.; Fall, A. How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. *PLoS ONE* **2013**, *8*, e62392. [CrossRef] [PubMed]