ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL094954

Special Section:
Fire in the Earth System

Climate-Driven Tree Mortality and Fuel Aridity Increase Wildfire's Potential Heat Flux

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Key Points:

- Tree mortality is increasing fuel availability by transitioning large amounts of biomass from live to dead pools
- The fuel moisture of dead biomass is more responsive to increasing temperature than live biomass
- Changing climate is increasing the amount of energy stored in biomass that can be released as heat during wildfire

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Goodwin, M. J., Zald, H. S. J., North, M. P., & Hurteau, M. D. (2021). Climate-driven tree mortality and fuel aridity increase wildfire's potential heat flux. *Geophysical Research Letters*, *48*, e2021GL094954. https://doi.org/10.1029/2021GL094954

Received 23 JUN 2021
Accepted 4 DEC 2021

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Abstract Wildfire is capable of rapidly releasing the energy stored in forests, with the amount of water in live and dead biomass acting as a regulator on the amount and rate of energy release. Here, we used temperature and fuel moisture data to examine climate-driven changes in fuel moisture content over the past three decades. We then calculated the changes in energy release (energy release component and fire radiant energy) for two forests that experienced drought and bark beetle mortality and were subsequently burned by wildfires. We found that mortality transitioned substantial amounts of biomass from live to dead pools. Coupled with climate-driven decreases in fuel moisture content, this change in fuel availability increased the amount of energy that could be released as heat during wildfire in these forests. Our results demonstrate that climate-driven tree mortality and fuel aridity may be increasing the amount of energy that is released during wildfire.

Plain Language Summary Assuming sufficient biomass and fuel continuity, the amount of water stored in the woody fuels of fire-prone forests regulates wildfire ignition and spread. Rising temperatures and widespread tree mortality are making fuels drier and increasing the ease of fuel combustion. While, previous research has focused on the relationship between increasing fuel aridity and wildfire activity, we propose that future research consider the combined effects of tree mortality and fuel aridity on fuel availability. We present a potential pathway for how climate change is increasing the energy that is released as heat during wildfire. This increase in the heat flux of wildfires creates a positive feedback for fire spread and may be a significant contributor to the unprecedented wildfire behavior we have seen in recent years.

1. Introduction

The proportion of biomass, or fuel, that is available for combustion during wildfire is a function of fuel moisture content (FMC), which governs the amount of time and energy needed to vapourize fuel moisture before ignition can occur (Brown & Davis, 1973; Rothermel, 1972). With rising temperatures, the FMC of both live and dead vegetation has been reduced, increasing the likelihood of wildfire ignition and spread in ecosystems that are not fuel limited (Abatzoglou & Williams, 2016). In addition, climate change has increased the frequency, duration, and severity of drought events in ecosystems around the globe (Allen et al., 2015), which also increases tree susceptibility to insect outbreaks and pathogens (Bentz et al., 2010; Weed et al., 2013). The extensive mortality that results from these disturbance agents leads to substantial increases in dead fuel loading. Because the FMC of dead fuels is typically much lower than live fuels and is more sensitive to changes in environmental conditions (Matthews, 2014), climate-driven tree mortality may be increasing the flammability of forests as it redistributes biomass from live to dead pools (Goodwin et al., 2020).

Following insect and drought-induced tree mortality, total biomass increases across dead fuel types (i.e., litter, 1-, 10-, 100-, and 1000-hr fuels and standing dead trees) as these dead trees begin to decay and fall (Goodwin et al., 2020; Stephens et al., 2018). Fine fuels (litter, 1-, 10-, and 100-hr) are the primary fuel for wildfire ignition and spread (Rothermel, 1972), as these small fuel classes dry quickly, making them readily available to burn over the duration of the fire season in dry forest types. Conversely, 1000-hr (fuels 3–8 inches in diameter) and 1000 + hour fuels (large logs) dry out over longer time scales, which has historically made them less available to burn over the course of the fire season due to the dampening effect of their moisture content. Climate change may be altering this control on fuel flammability as the FMC of these larger fuels decreases with rising temperatures and fuel aridity (Abatzoglou & Williams, 2016). As a result, the dead fuel pools that receive the largest proportion

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of biomass from tree mortality are becoming increasingly available to burn, with important consequences for the amount of energy that can be released during wildfire.

In wildfire risk assessments, FMC is used to determine the energy release component (ERC, J m-2) for a given area, or the amount of energy that can be released during the flaming spread of a wildfire (Finney et al., 2011). FMC also regulates the proportion of heat energy that is transferred through radiation during wildfire, with fire radiant energy (FRE) increasing as FMC decreases (Brown & Davis, 1973). As a result, reductions in FMC from tree mortality and rising temperatures may be increasing the amount of energy that can be released during wildfire. Because radiant heat energy is primarily responsible for pre-heating and dehydrating fuels surrounding a wildfire, increases in FRE release can facilitate fuel ignition and wildfire spread (Linn, 1997). Consequently, fires that occur where there is a surplus of standing dead and 1000-hr fuels may release large quantities of the energy stored in this biomass as heat, resulting in fires characterized by their unprecedented size, intensity, and rates of spread.

Globally, wildfire activity has been increasing, with recent years being notable for individual fires breaking records for size, spread and plume formation. The combined effects of tree mortality and rising temperatures on FMC may, in part, be responsible for the substantial energy release that has characterized modern wildfires. Here we present two case studies from the 2020 fire season in the western United States. The 153,738 ha Creek Fire in California's Sierra Nevada occurred in an area where the 2012–2016 drought and subsequent bark beetle outbreak resulted in widespread tree mortality (Pile et al., 2019). Similarly, the 84,443 ha Cameron Peak Fire in the Colorado Rocky Mountains burned through forest with large numbers of bark beetle-killed trees (Meddens & Hicke, 2014). While, the mixed-conifer forests in California's Mediterranean climate are seasonally dry and Colorado's lodgepole pine forests are cool and wet, fire intensity in both areas is influenced by fuel moisture and dead fuel loading from tree mortality (Stephens et al., 2018). This dead fuel loading, coupled with rising temperatures and fuel aridity, may have contributed to the unprecedented fire spread and energy release observed during these large fire events (Stephens et al., 2018), an area of active research. Here, we use data from the southern Sierra Nevada and Colorado Rocky Mountains to estimate the combined effects of climate-driven tree mortality and rising temperatures on FMC and fuel availability prior to these two fires. We then use these data to estimate how dead fuel loading combined with temperature driven reductions in FMC may contribute to the amount of heat energy released during wildfire.

2. Materials and Methods

We used US Forest Service Forest Inventory and Analysis (FIA) plot data to estimate increases in dead tree basal area pre- and post-disturbance for mixed-conifer forests in the southern Sierra Nevada and lodgepole pine forests in Colorado. These forest types occupied the majority of the burn area in the Creek Fire and Cameron Peak Fire, respectively. For the southern Sierra Nevada, we used the rFIA package (Stanke et al., 2020) to select plots that were located in Fresno, Madera, Mariposa, Kern and Tulare counties. We then selected for plots that contained at least one of the five conifer species found in the Sierran mixed-conifer forest type (*Abies concolor*, *Abies magnifica*, *Calocedrus decurrens*, *Pinus lambertiana* and *Pinus jeffreyi*). For lodgepole pine forests in Colorado, we used the rFIA package to select all plots in Colorado that contained lodgepole pine (*Pinus contorta v. contorta*). For each region, plots were further selected based on whether measurements occurred both before and after the disturbance event in question. In the southern Sierra Nevada, we identified plots that had been measured prior to and after the 2012–2016 drought, which led to significant overstory tree mortality (Pile et al., 2019), for a total of 118 plots. In the Rocky Mountains we identified plots that were measured before and after the 2007–2009 peak in mountain pine beetle mortality (Meddens & Hicke, 2014) for a total of 173 plots. The fuel loading used to calculate FRE and biomass consumed in the southern Sierra Nevada is the average change in dead biomass over the 2012–2016 drought period for the southern Sierra Nevada FIA plots (25,460.75 ± 54,918.87 kg ha^{-1}, Calculation 4 in Supporting Information S1). The change in dead biomass in the Rocky Mountain FIA plots following the 2007–2009 beetle mortality peak was used to calculate changes in fuel availability and FRE in the Colorado Rocky Mountains (24,215.19 ± 30,024.86 kg ha^{-1}, Calculation 4 in Supporting Information S1).

We used daily maximum temperature, 1000-hr fuel moisture, and ERC data from GRIDMET (Abatzoglou, 2013) to assess changes in 1000-hr FMC and ERC over the past three decades within the footprints of the Creek Fire and Cameron Peak Fire. Additionally, we used 1000-hr fuel moisture data from the southern Sierra Nevada

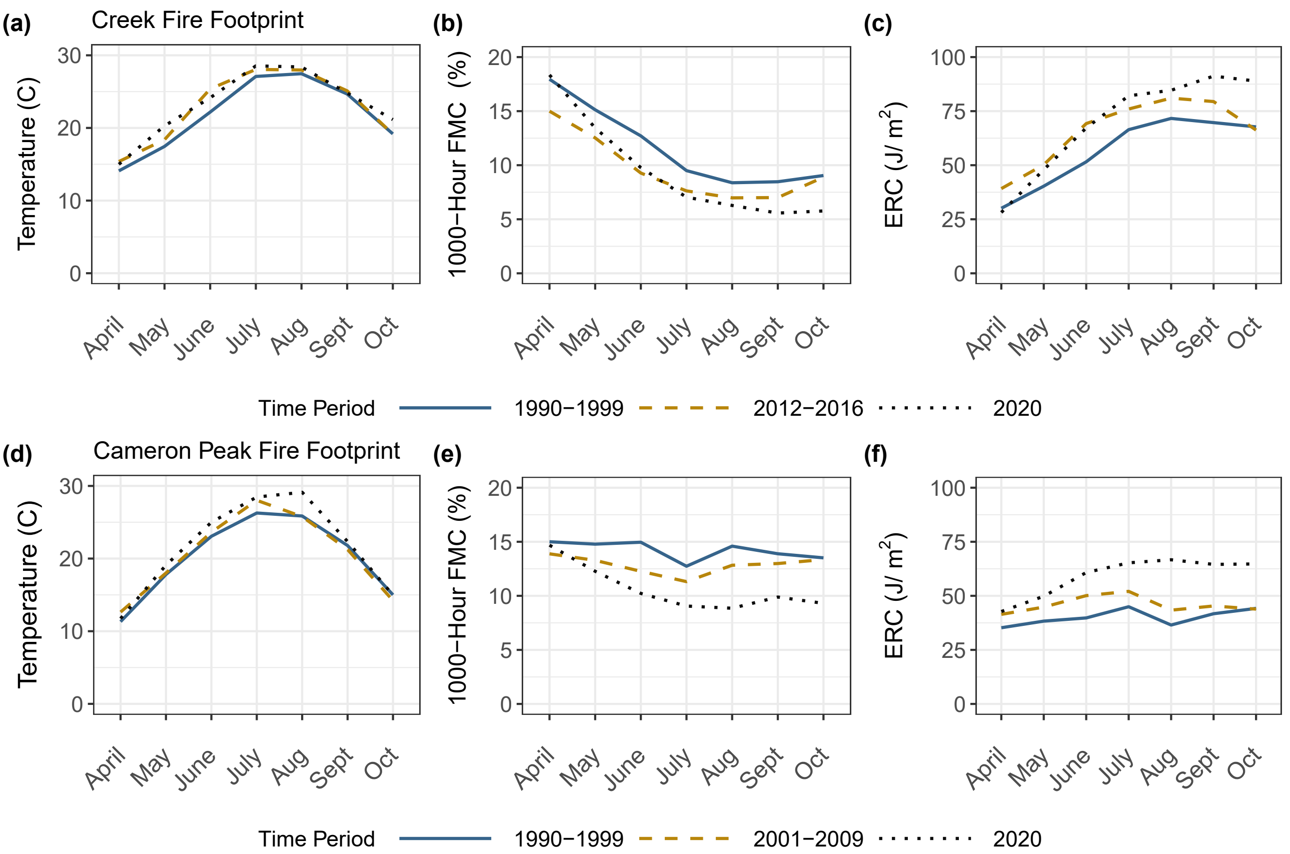

Figure 1. Average monthly temperature maximums (C), average 1000-hr fuel moisture content, and average energy release component for the footprints of the Creek Fire (a–c) and Cameron Peak Fire (d–f) based on GRIDMET data. Time series for each site include 1990–1999, 2012–2016 or 2001–2009 (the respective drought periods for each site) and 2020.

available through the Wildland Fire Assessment System (WFAS) and corresponding temperature data from the Remote Automatic Weather Station (RAWS) Climate Archive to develop monthly fuel moisture and temperature averages for 1998–2002, 2012–2016, and 2020. For the Colorado Rocky Mountains, we used 1000-hr and lodgepole pine (*Pinus contorta v. contorta)* fuel moisture data from WFAS and corresponding RAWS temperature data for 2006–2010 and 2016–2020. We focused on 1000-hr fuels because smaller fuels (1–100-hr) are usually seasonally dry and readily ignite in these western US forest types, while changing climate conditions are most likely to increase large fuel combustion, affecting wildfire's energy release. We used 1000-hr FMC as a conservative estimate of the FMC of standing dead trees. This is based on previous research that has postulated that the moisture content of standing dead wood is equal to or less than that of downed dead fuel (Harmon et al., 2011). FMC was converted to water content to calculate FRE and biomass consumed using the equations outlined in Smith et al. (2013). FRE provides a conservative estimate of the heat flux during wildfire since heat can also be transferred through convection and conduction. The heat flux during wildfire includes both latent and sensible heat but here we use heat flux to refer to the sensible heat flux. Database citations, code, and calculations can be found in Supporting Information S1.

3. Results

Compared to the end of the 20th century (1990–1999), monthly temperature maximums (April to October) in the southern Sierra Nevada and Colorado Rocky Mountains have increased in recent years (Figures 1a and 1d, Figure 2a), with corresponding decreases in 1000-hr FMC (Figures 1b and 1e, Figure 2b). Decreases in FMC during periods of drought (2012–2016 in the Sierra Nevada and 2001–2009 in the Colorado Rockies) and in 2020 resulted in higher calculated ERC values for the areas where the Creek Fire and Cameron Peak Fire occurred

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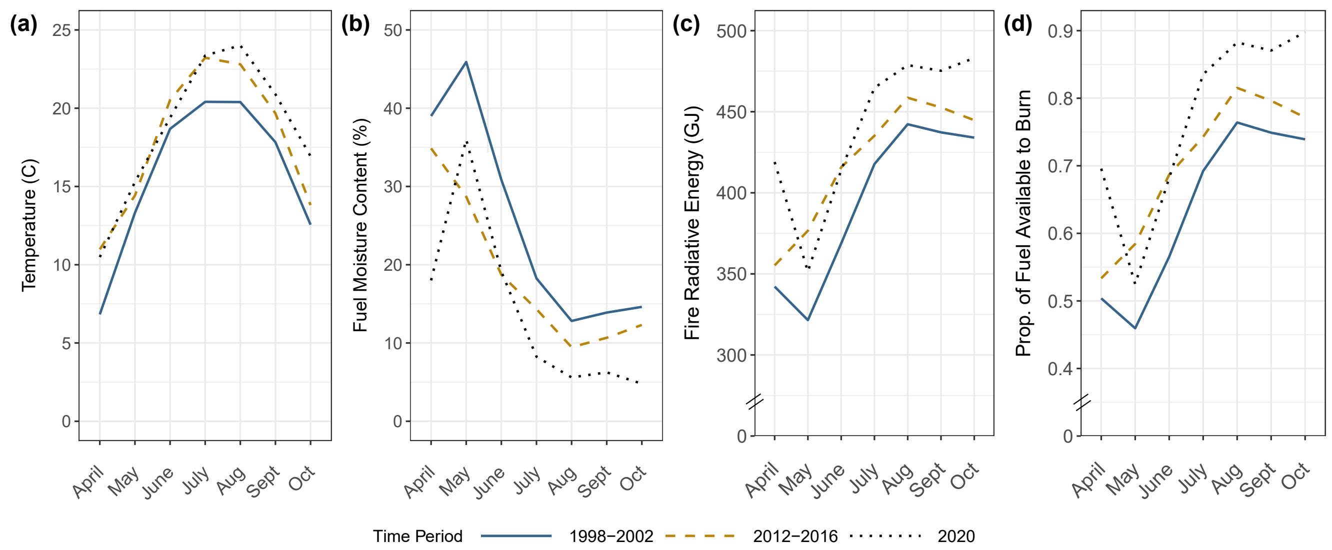

Figure 2. (a) Average monthly temperature (c), (b) average 1000-hr fuel moisture content (FMC), (c) calculated fire radiative energy, and (d) calculated fuel consumption for the southern Sierra Nevada during three time periods: 1998–2002, 2012–2016, and 2020. The extinction FMC for dead fuels, or the FMC at which fire can no longer spread, is ∼30%. Calculations are derived from Wildland Fire Assessment System fuel moisture data and Remote Automatic Weather Station climate data.

(Figures 1c and 1f). In the southern Sierra Nevada, decreases in FMC also resulted in higher calculated FRE and a greater proportion of biomass available to burn, suggesting that temperature-driven reductions in dead FMC increased both fuel availability and the amount of energy available for release in the region where the Creek Fire burned (Figures 2b–2d, Calculation 1 in Supporting Information S1). In addition, 1000-hr FMC in the southern Sierra Nevada dropped below the ignition threshold of 30% earlier in the season during both the 2012–2016 drought and in 2020 when compared to 1998–2002 (Figure 2b).

Both the southern Sierra Nevada and Colorado Rocky Mountains experienced substantial tree mortality prior to the Creek and Cameron Peak fires (Figures 3a and 3b). In the Colorado Rocky Mountains, we found that a 5% reduction in FMC would result in a 7% increase in dead fuel availability compared to a 1% increase in live fuel availability (Calculation 2 in Supporting Information S1), suggesting that climate-driven reductions in FMC will disproportionately increase the availability of 1000-hr dead fuels compared to live fuels. Further, we estimated that higher temperatures coupled with dead fuel loading from beetle mortality resulted in a 55% increase in fuel availability and a two-fold increase in potential FRE release in the region where the Cameron Peak fire occurred (Calculation 3 in Supporting Information S1).

4. Conclusions

Globally, forests have experienced widespread tree mortality from climate-driven disturbance events which has transitioned large amounts of biomass from live trees to dead fuels (Allen et al., 2010; Hood et al., 2021; Stephens et al., 2018). Because fuel moisture is the primary control on fuel availability, this transition is increasing the proportion of biomass that is readily available to burn in these mortality-affected forests. While standing dead trees, 1000-hr, and fine fuels (1-, 10-, and 100-) all increase following widespread tree mortality, the additions from fine fuels are relatively small as a proportion of total biomass when compared to dead trees and 1000-hr fuels. Unlike fine fuels, which become readily available to burn each year in forests that have a prolonged dry season, increases in the flammability of standing dead and 1000-hr fuels are largely a function climate-driven decreases in FMC. As temperatures and precipitation deficits continue to rise with climate change, there will be substantial reductions in the amount of water stored in the biomass of fire-prone systems (Abatzoglou & Williams, 2016; Flannigan et al., 2016). By removing the dampening effect of FMC, especially in large dead fuels, climate change is not only increasing the overall and seasonal flammability of these systems but is also increasing the amount of energy stored in biomass that can be released as heat when wildfire occurs. While, the empirical data we present here are limited to the southern Sierra Nevada and the Colorado Rocky Mountains, and should not be extrapolated

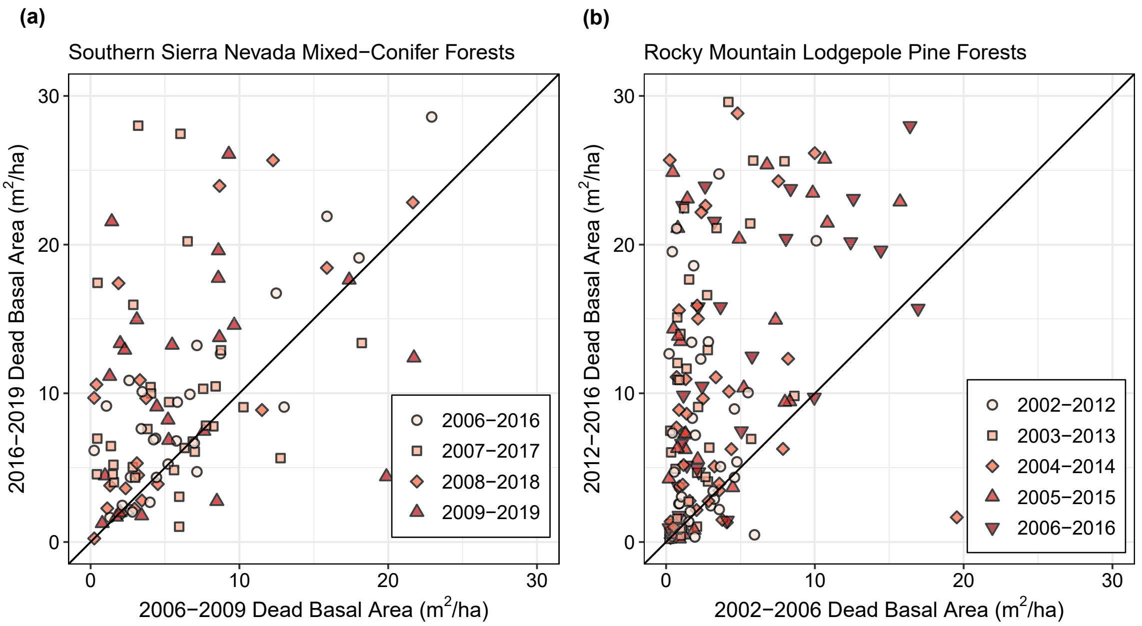

Figure 3. Increases in dead tree basal area (m^2 ha^{-1}) following disturbance events. The 1:1 trend line represents no change in dead tree basal area before and after the disturbance. Plots with the same color/symbol are grouped by 10-year measurement period. Points represent Forest Inventory and Analysis (FIA) plots measured: (a) Before and after the 2012–2016 California drought. Points represent mixed-conifer FIA plots in the southern Sierra Nevada. (b) Before and after peak Mountain Pine Beetle mortality in the Colorado Rocky Mountains (2007–2009). Points represent lodgepole -pine FIA plots in Colorado.

to other forest types, our results suggest that climate-driven tree mortality and fuel aridity have the potential to increase both fuel availability and wildfire's heat flux in seasonally dry fire-prone ecosystems (Figures 1–3). Systems that receive higher precipitation or typically have shorter fire seasons than our study areas will likely have lower amounts of biomass available to burn because increased fuel moisture will allow the larger fuel classes to remain resistant to combustion.

Combined with fire transport models that relate radiant heat energy release to fire behavior and spread (Linn, 1997), our results suggest that widespread tree mortality and rising temperatures may be significant contributors to the unprecedented wildfire behavior witnessed in recent years. The substantial amount of heat energy released during these fires can generate a positive feedback with wildfire spread (Stephens et al., 2018) producing wildfires capable of generating their own weather, further increasing wildfire spread and making them incredibly difficult to control. Consequently, the abundant dead and dry fuel loads produced by climate-driven mortality and fuel aridity can result in wildfires that are perpetuated not only by available fuels, but by the substantial amounts of heat energy they release back to the atmosphere.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Supplemental calculations, supporting code, and references to publicly available data are available at https://doi.org/10.5061/dryad.rjdfn2zbr

Acknowledgments
Support for this project came from California Department of Forestry and Fire Protection as part of the California Climate Investments Program, grant #8GG14803.

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